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Mobile market performance and market structure in Europe during the 4G era

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Mobile market performance and market structure in Europe during the 4G era

Abate, Serafino; Bahia, Calvin; Castells, Pau

2020

Abstract

This study evaluates the impact of competition on quality, innovation and price in Europe's mobile communications market during the 4G era (2011-18). Our results indicate that European mobile users in more concentrated markets benefitted the most from higher network quality, particularly with regard to download speeds. We find that dispersion of fixed costs and assets among a greater number of players can result in diseconomies of scale and a less efficient use of resources, which translates into lower network performance, to the detriment of consumers. We also find evidence of investment per operator being greater in markets with higher profit margins, which are also typically more concentrated markets.

JEL Classifications: K20 - General; L10 - General; L40 - General; L96 - Telecommunications

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1. Introduction

The mobile market in Europe has started to come to the end of its significant phase of investment in fourth generation (4G) mobile networks. 4G network coverage surpassed 90% of the European population by 2016¹. As a result, 4G accounted for more than half of mobile connections across Europe by 2019. Mobile operators in Europe are now turning their attention to 5G network investment, with networks launching in Switzerland and the UK in early 2019.

Market structure has evolved with each generation of mobile technology. 2G networks started off with individual network operators building up their customer base in telecommunication markets where mobile use was nascent. By the time 3G networks were introduced, regulators had started to incentivise new entry into markets, including the use of reserved spectrum. In addition, mobile virtual network operators (MVNOs), who lease capacity from network operators, increased in volume and made significant inroads into many voice and SMS markets.

4G introduced a significant increase in data capacity for consumers. Operators sought to reduce the cost of network rollout in this generation as the primary source of revenues moved from unit-priced minutes and SMS' to monthly or top-up data packages. One way to reduce network costs was the increase in network sharing mechanisms between individual network operators in order to gain efficiencies in network construction. The other was through market consolidation, via mergers and acquisitions.

There have been seven approved mergers in Europe² since 2010 – in the United Kingdom, Austria, Ireland, Germany, Norway, Italy and most recently the Netherlands. In the same period, there have also been five major entries into the mobile markets – in France, the Netherlands, Norway, Italy and Slovakia.

However, during this period Europe's chief competition authority, the Directorate General for Competition of the European Commission, also rejected a proposed merger in the United Kingdom on the grounds that the competition concerns outweighed the perceived potential benefits³. Additionally, a proposed merger was withdrawn in Denmark on the expectation that the European Commission would not clear it without significant remedies⁴.

This paper seeks to investigate the relationship between market structure and market outcomes, focussing on how market concentration impacts market outcomes and mobile networks performance.

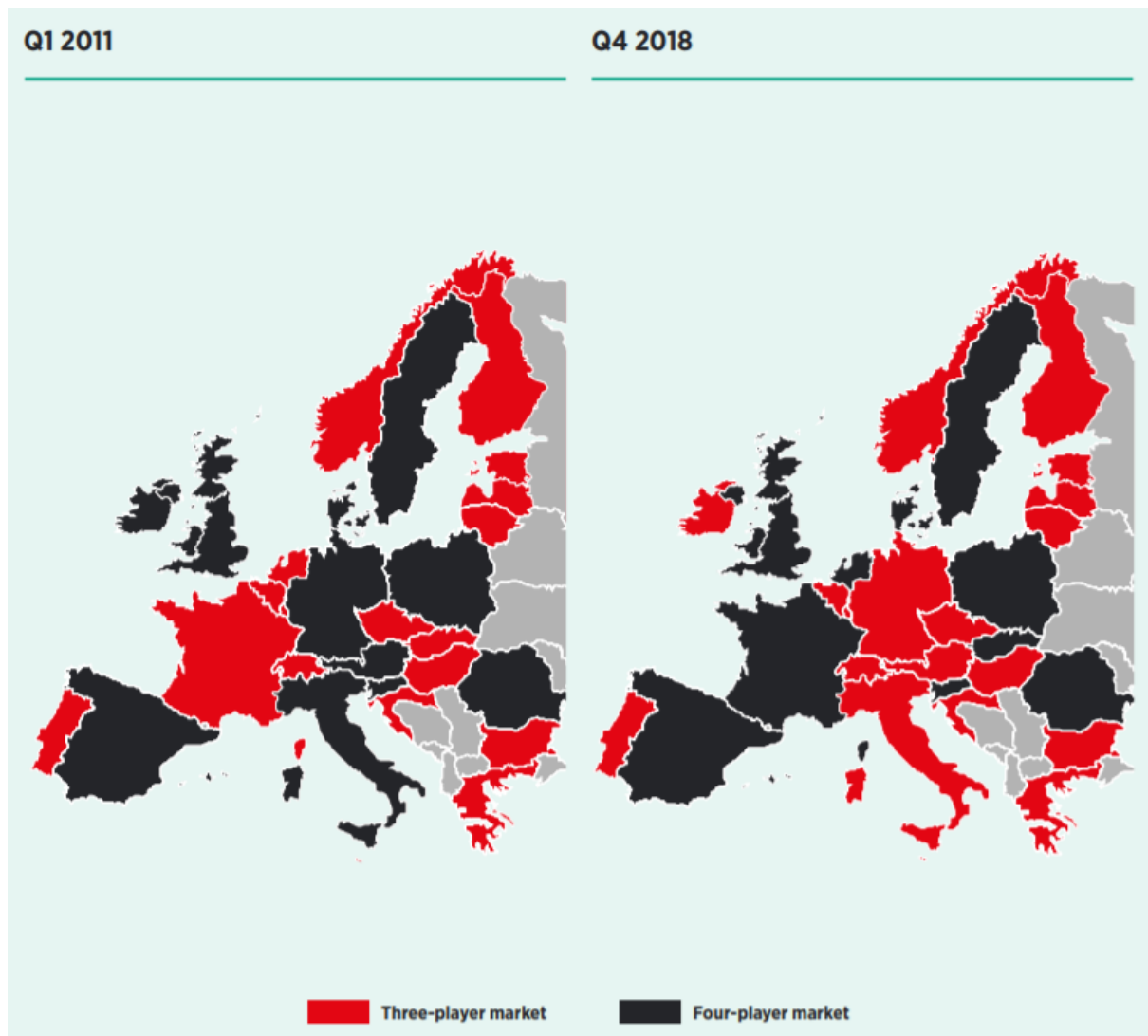
¹ Source: GSMA Intelligence

² The data we studied covers 29 European countries – 27 out of the 28 members of the European Union along with Norway and Switzerland (Cyprus was not used due to the existence of two practical mobile markets on the island). We included operators that had a market share greater than 3 per cent at some point in the period of analysis. This was for two reasons: (i) to ensure that we only took into account operators with a significant presence in the national market, and; (ii) to ensure that the operators in our sample had sufficient network quality data. The operators included in our analysis accounted for more than 99% of mobile connections in the 29 countries over the period.

³ http://ec.europa.eu/competition/mergers/cases/decisions/m7612_6555_3.pdf

⁴ https://europa.eu/rapid/press-release_STATEMENT-15-5627_en.htm

Figure 1: Number of major operators in European markets (2018)



2. Literature review

Historically, competition has been measured using indicators such as the number of players or measures of market concentration (e.g. market shares and HHI). However, the relationship between the number of players and outcomes such as quality, innovation and prices is complex. Economic theory suggests that an increase in concentration can have both positive and negative effects, and that it depends on the particular circumstances, the incentives of players and consumer attitudes to products and services.

Lower market concentration indices can be associated with greater incentives to lower prices and improve quality of service⁵. However, concentration levels that are too low can generate dynamics that cancel out these positive competitive effects⁶. In particular, market structures with a larger number of operators can undermine operators' scale, push up average deployment costs, and decrease margins and returns on investment. This can reduce the ability and incentive to invest in improving network quality and innovation, and limit operators' ability to minimise costs.

The latest empirical research has shown that having fewer operators in a market can bring more investment for operators⁷. No study to date has found that higher market concentration reduces operator investment. Other recent empirical studies have also found a positive impact of mergers, operator scale and more concentrated markets on network coverage and network speeds⁸.

The evidence with regard to pricing impacts is mixed, with some studies suggesting mergers or increased concentration can increase consumer prices while others suggest they can drive price reductions. The different findings are often due to the choice of pricing metric and the methodologies employed. Figure 2 presents a summary of some of the relevant literature.⁹

⁵ Motta, Tarantino 2017, "The effect of horizontal mergers: when firms compete in prices and investments" and Federico, Langus, Valetti 2018, "Horizontal Mergers and Product Innovation"

⁶ Noting that firms in higher concentrated markets may engage in business expansion: Jullien, Lefouilli 2018, "Horizontal mergers and innovation" and Bourreau, Jullien 2017, "Mergers, investments and demand expansion"

⁷ See for example Genakos, Valletti, Verboven 2018, "Evaluating market consolidation in mobile communications"

⁸ This includes the evaluation of a European merger in Austria, and a study looking at investment, network quality and market structure in Central America. See:

www.gsma.com/publicpolicy/evaluation_hutchison_orange_merger_austria and

www.gsma.com/publicpolicy/driving_mobile_broadband_in_central_america

⁹ A more detailed literature review can be found in in Fruits, Hurwitz, Manne, Morris and Stapp, '[A Review of the Empirical Evidence on the Effects of Market Concentration and Mergers in the Wireless Telecommunications Industry](#)' (ICLE, 2019)

Figure 2: Summary of assumed outcomes under *higher* market concentration

Study	Quality and Innovation	Investment	Price	Scope
Motta, Tarantino, 2017	NA	Lower	Higher	Theoretical
Federico, Langus, Valetti, 2018	NA	Ambiguous	NA	Theoretical
Jullien, Lefouili 2018	NA	Ambiguous	NA	Theoretical
Bourreau, Jullien 2017	NA	Higher	Higher	Theoretical
Genakos, Valletti, Verboven, 2018	NA	Higher per operator, Inconclusive at market level	Higher (basket price)	OECD countries, 2002-2014
GSMA (2017)	Higher	NA	NA	Austria, 2012 Merger
GSMA (2019)	Higher	"Inverted-U"	NA	Central America, 2013-2016
Houngbonon & Jeanjean (2016b)	NA	"Inverted-U" at operator level	NA	110 operators, 2005 - 2012
HSBC (2015)	NA	"Inverted-U" at operator level		66 markets, 2003 - 2013
WIK (2015)	NA	No effect	NA	12 European and non-EU countries, 2005-2013
DG Comp (2015)	NA	NA	Higher (basket price)	Netherlands, 2007 merger
RTR (2016)	NA	NA	Higher (basket price)	Austria, 2012 merger
Houngbonon (2015)	NA	NA	Lower (unit price)	Austria, 2012 merger
HSBC (2015)	NA	NA	Lower (unit price)	Austria, 2012 merger

Building on these studies, we look at the impact of competition on both price and non-price outcomes in the mobile market in Europe during the 4G era.

3. Data

Overall, we have looked at data covering the period Q2 2011 to Q4 2018, which covers the majority of the '4G era' in Europe. The data covers 29 European countries – 27 out of the 28 members of the European Union¹⁰ along with Norway and Switzerland.

Figure 3: Scope of operators and countries, Q2 2011 to Q4 2018

Country	Number of operators	Country	Number of operators
Austria	4 -> 3	Lithuania	3
Belgium	3	Luxembourg	3
Bulgaria	3	Malta	3
Croatia	3	Netherlands	3 -> 4*
Czech Republic	3	Norway	3**
Denmark	4	Poland	4
Estonia	3	Portugal	3
Finland	3	Romania	4
France	3 -> 4	Slovakia	3 -> 4
Germany	4 -> 3	Slovenia	4
Greece	3	Spain	4
Hungary	3	Sweden	4
Ireland	4 -> 3	Switzerland	3
Italy	4 -> 3***	United Kingdom	4
Latvia	3		

* In January 2019, Tele2 and Deutsche Telekom completed a merger in the Netherlands. However, as our analysis covers the period to 2018q4, we do not incorporate the effects of the merger.

**Norway experienced a merger (3 to 2) which was immediately followed with the expansion of a new third player Ice (2 to 3)

***Following the merger in Italy between Hutchison and Wind, a new entrant (Iliad) entered the market in 2018. However, it only became a significant player in 2019. For simplicity, we leave Italy as a three-player market at the end of our analysis.

¹⁰ Cyprus was not used due to the existence of two practical mobile markets on the island

Figure 4: Summary statistics

Variable	Source	Observations	Mean	Standard Deviation	Minimum	Maximum
Average download speeds (Mbps)	Speedtest Intelligence, Ookla	2,964	18.10	14.28	0.19	77.81
Average upload speeds (Mbps)	Speedtest Intelligence, Ookla	2,964	6.86	5.18	0.08	27.44
Average latency (ms)	Speedtest Intelligence, Ookla	2,964	112.15	88.10	19.46	654.83
4G coverage	GSMA Intelligence	2,292	0.75	0.28	0.02	1
Capex per connection (Euros)	GSMA Intelligence	1,825	10.57	18.45	0.20	638.32
ARPU (Euros)	GSMA Intelligence	2,921	16.14	8.41	1.51	52.90
Share of population in rural areas (%)	World Bank	3,038	26.63	12.43	2.00	47.12
GDP per capita (euros, chain linked volumes 2010)	Eurostat	3,035	6985.67	4470.38	1100	20800
Total spectrum holdings (MHz)	GSMA Intelligence	3,038	648.34	161.52	226.4	870
HHI	GSMA Intelligence	3,038	3275.90	505.36	2330	4620
EBITDA	GSMA Intelligence	1,986	0.27	0.14	-0.89	0.6

3.1 Network Coverage

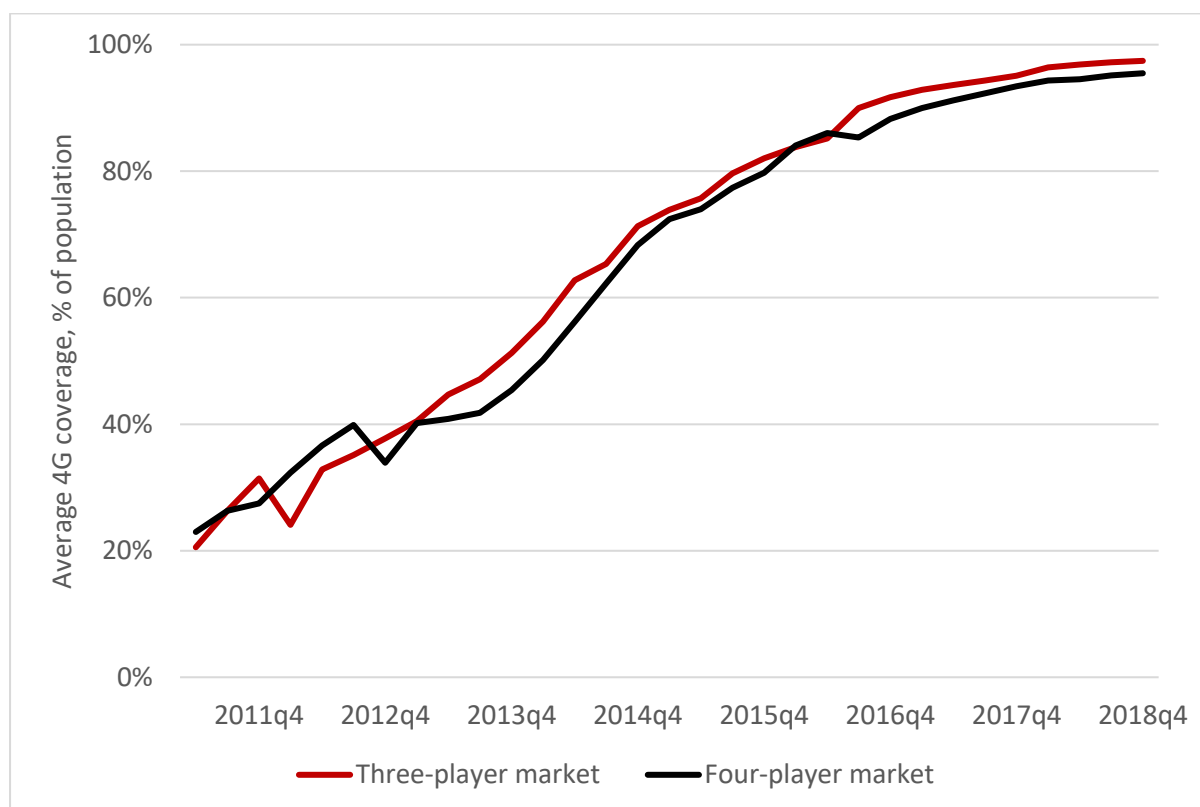
Data on network coverage is sourced from GSMA Intelligence and measures the proportion of the population resident in an area where 4G networks are available (i.e. coverage by population rather than by geographic area). The data is gathered from operators and regulators. Where coverage is not reported in each quarter, data is estimated by GSMA Intelligence modelling.¹¹

4G coverage trends

Regardless of market type, most European operators had achieved 4G coverage of 80% of their population by mid-2015 and 90% by the end of 2016. For most of the period, three-player markets achieved slightly accelerated network expansion, though the difference between three- and four-player is not notably significant.

¹¹ Further information on GSMA Intelligence data and modelling can be found [here](#).

Figure 5: 4G coverage trends



Source: GSMA Intelligence

3.2 Network Quality

We used data from Speedtest Intelligence® (sourced from Ookla®) to obtain network performance at an operator level. The Speedtest consumer-initiated testing platform allows mobile users to initiate a ‘speed test’ to measure network performance at any given time.¹² Each time a user runs a test, they receive a measurement for download speed, upload speed and latency. The test also records the consumer’s location, the network operator and the technology being used at the time of the test.¹³ Each year, Speedtest is used by 500 million unique users globally, and an average of 10 million consumer-initiated performance tests are run per day.

Using these test results, Ookla calculates the average (mean) network performance metric across all users in each quarter at both the country and operator level. In this study, we focussed on:

- Download speeds (higher speeds allow consumers to download content more quickly and use data-intensive applications and content, such as video)
- Upload speeds (higher speeds enable consumers to share more content and experience better performance of services such as online gaming)

¹² <https://www.speedtest.net/apps/mobile>

¹³ For further information on the Speedtest methodology, see <https://www.speedtest.net/insights/blog/testing-methods-sampling/>

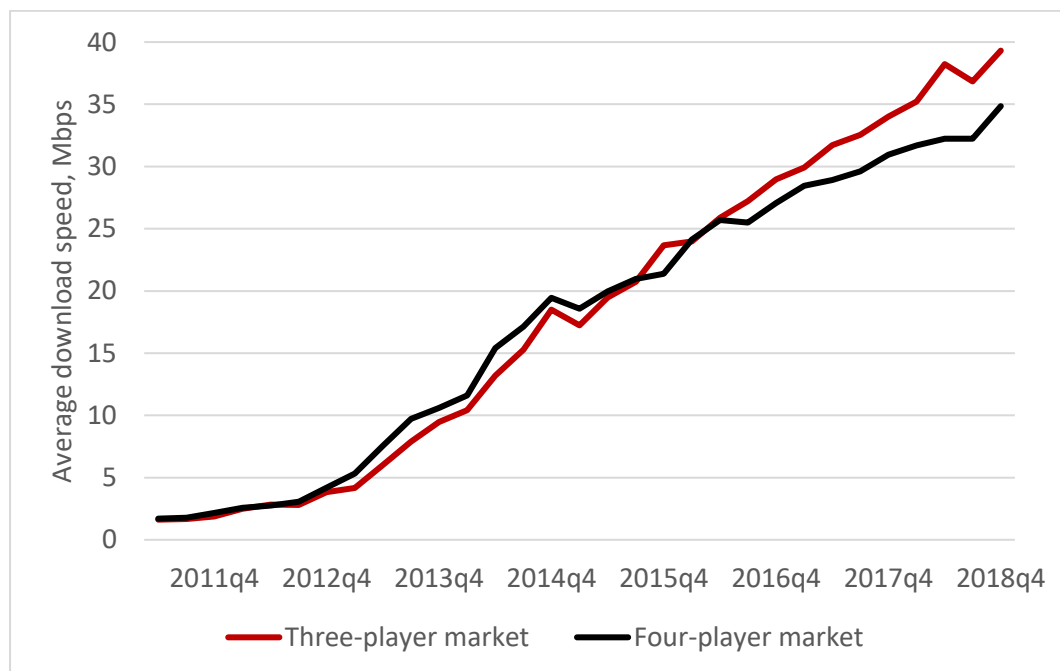
- Latency (relevant for services that require short delays such as video calls, Voice over IP or online gaming)

Network quality trends

Figure 6 shows that download speeds increased from below 5 Mbps in 2011 to more than 30 Mbps on average by the end of 2018. At this point, three-players markets were outperforming four-players markets by almost 5 Mbps (or 13% higher). The difference between three-players and four-players markets is also apparent when assessing upload speeds, which were 16% higher in three-players markets than in four-players markets in 2018 (Figure 7). The two network quality measures also show a distinct change in the gap between three- and four-players markets in the second half of the 4G era, from late 2015 onwards.

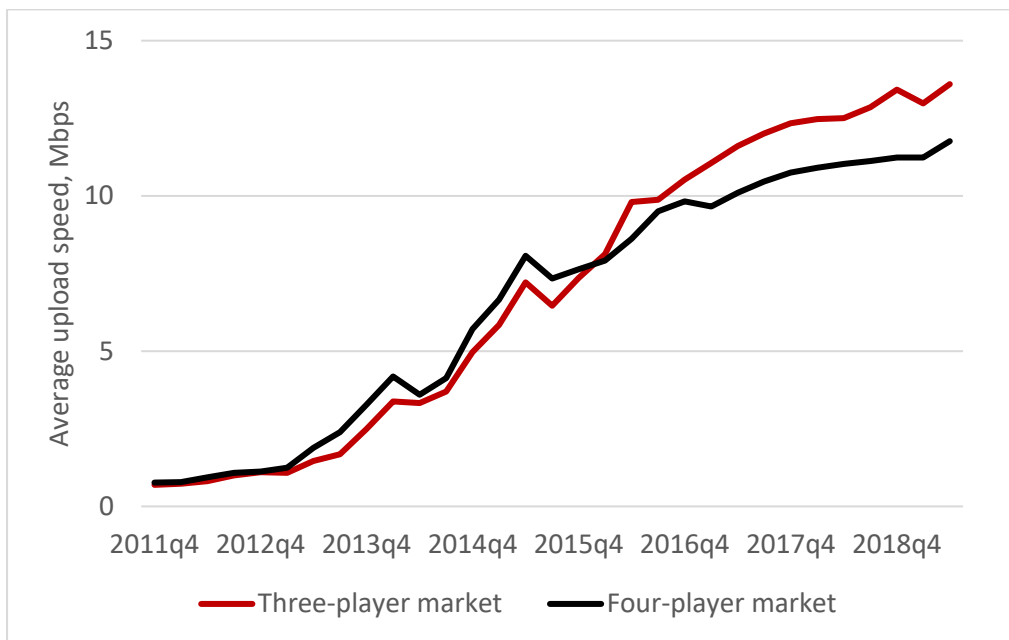
One of the potential reasons for this is that by this point, most European operators had achieved widespread rollout of 4G coverage (as shown above in Figure 5). By end of 2015, average 4G coverage for operators in the sample was had reached more than 80%. Network performance at the beginning of a roll-out of new technology is variable as consumer take-up is low and the initial effort is to expand network coverage as much as possible. After this initial phase, operators focus their investment efforts on capacity improvements.

Figure 6: Download speeds by market type



Source: GSMA Intelligence

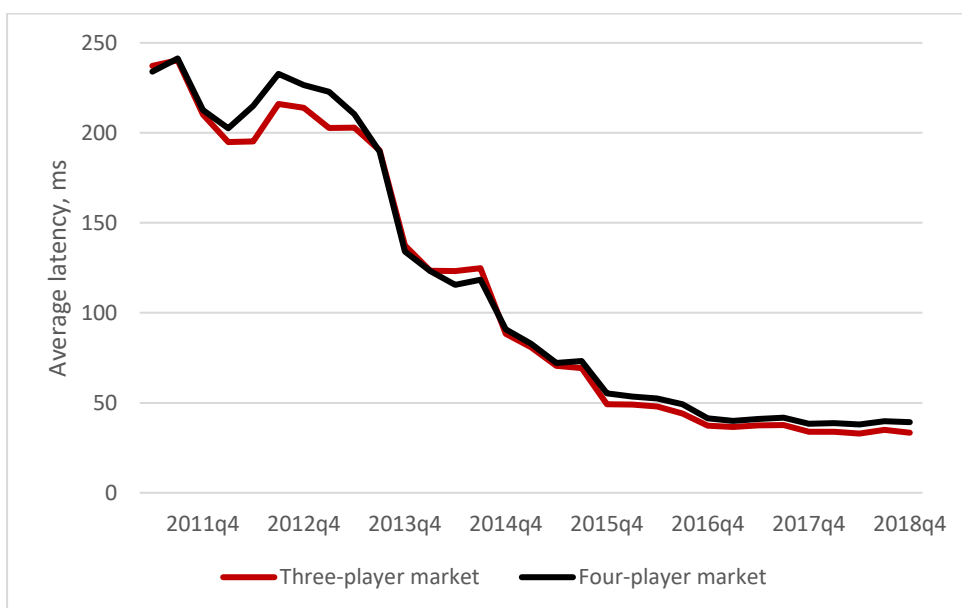
Figure 7: Upload speeds by market type



Source: GSMA Intelligence

Overall latency decreased dramatically from the beginning of the 4G era as consumers switched to 4G services (Figure 8). The difference between three-player and four-player markets appear to follow three phases: in 2011-2012 average latencies were lower in three-player markets; in 2013-2015 they were very similar, and; after 2015 latencies fell more quickly in three-player markets (in line with the differences we see in network speeds). By the end of 2018, latencies were 15% lower in three-player markets.

Figure 8: Average latency, ms



Source: GSMA Intelligence

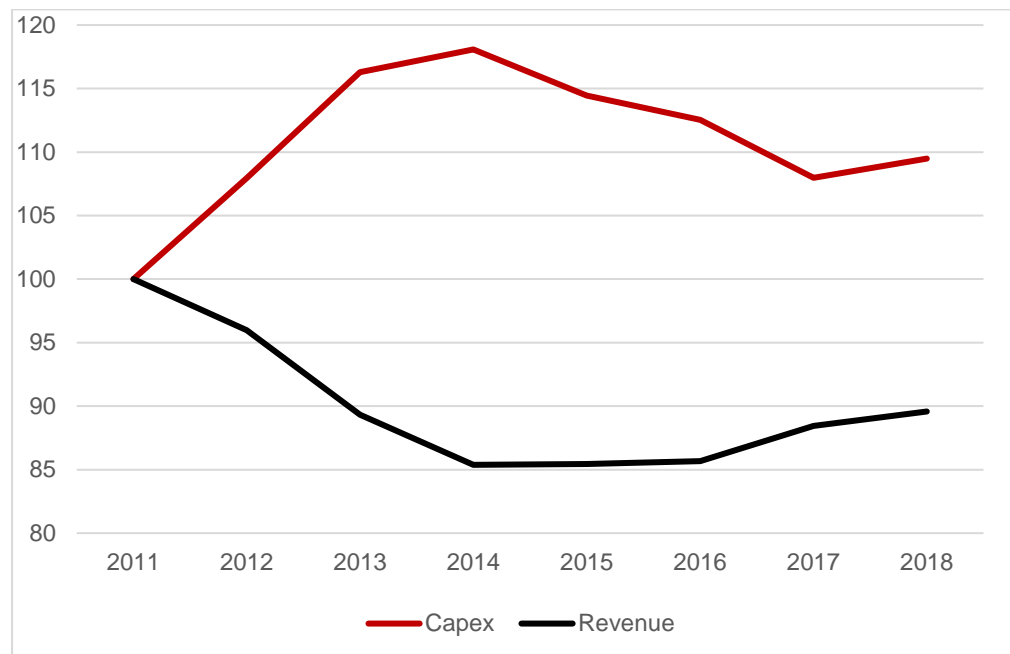
3.3 Investment

In previous studies, investment has been used as a proxy for network quality and innovation. While it is preferable to consider actual outcomes (such as download speeds and coverage levels) than inputs (such as investment), we can assess investment by measuring changes in capital expenditure. We use data from GSMA Intelligence on capital expenditure at an operator level. This is primarily sourced from operator-reported capex data, though this is more limited in availability than data on network quality and coverage (see Figure 4).

Investment and revenue trends

There was a sharp decline in revenues observed at the beginning of the period, but this stabilised across most markets from 2014 onwards (see Figure 9).

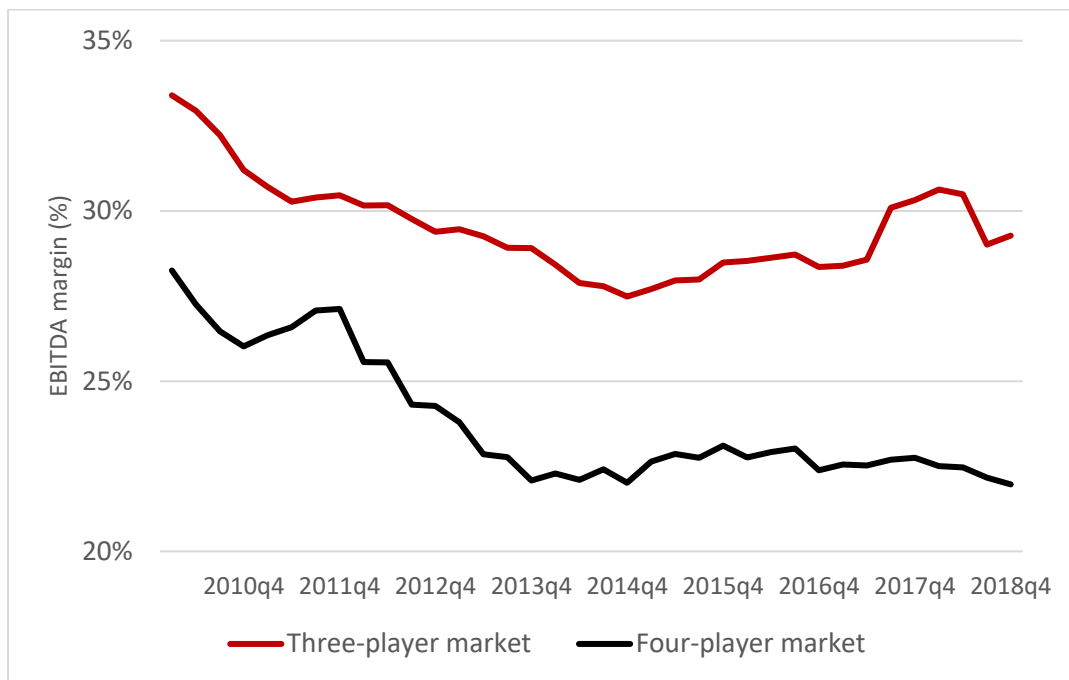
Figure 9: Capital expenditure and Revenue (Index = 100 in 2011) of 29 European countries



Source: GSMA Intelligence

This helped improved the financial position of all operators but more markedly so in three-player markets. Figure 10 show that profitability increased in three player markets to a greater extent after 2015.

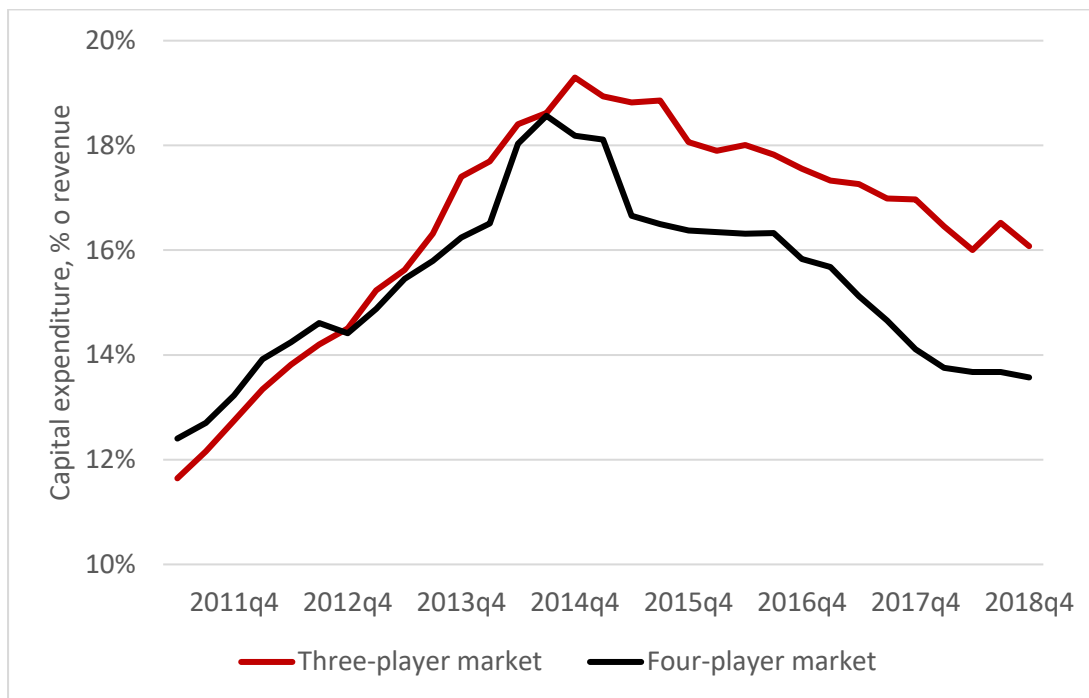
Figure 10: Profit margins



Source: GSMA Intelligence. Based on net profit margin data for an average of 22 operators per quarter. EBITDA margin data for an average of 68 operators per quarter.

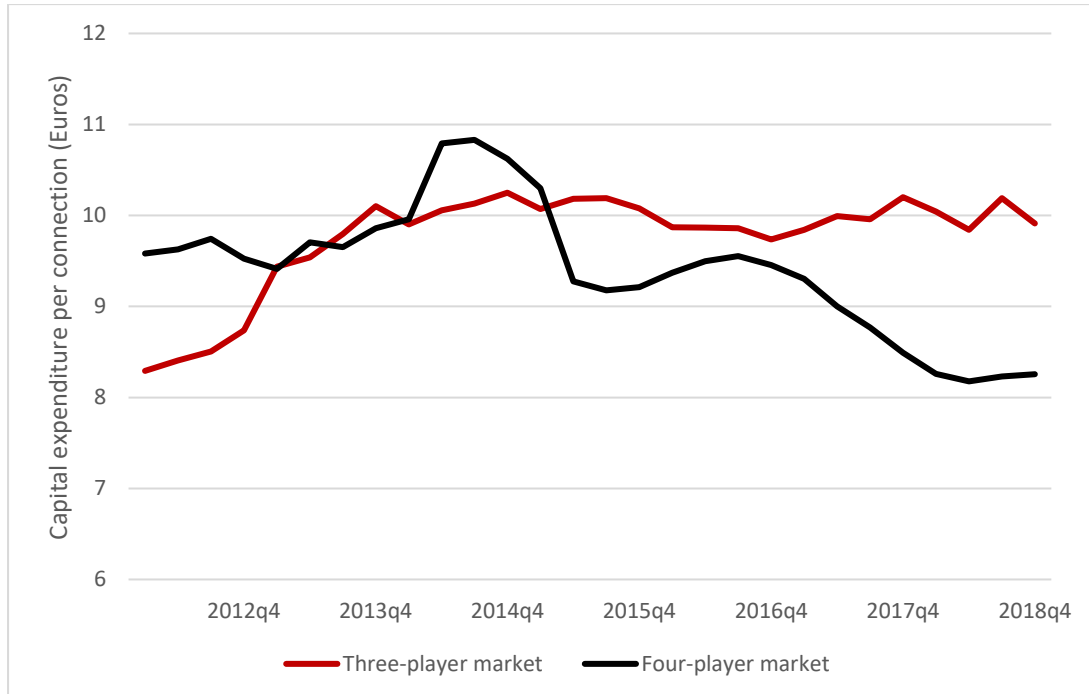
Improved profit margins can enable greater investments, and Figures 11 and 12 shows that from 2015 operators in three-player markets invested more per connection and as a proportion of revenues. The fact that operators in 3-player markets had higher profit margins and investment levels means that they could have invested more quickly in newer and faster technologies (such as LTE Advanced).

Figure 11: Capital expenditure as a % of revenue (country averages)



Source: GSMA Intelligence

Figure 12: Capital expenditure per connection (four-quarter moving operator averages)



Source: GSMA Intelligence

3.4 Market concentration measures

There are different of measures of market concentration that can be used to determine how a market is structured. We consider the following:

- Number of players: we use a 3% connections share threshold to count the number of major players in each market. During the 4G era, Europe consisted of three- and four- major player markets.
- Herfindahl-Hirschman Index: the primary measure of market concentration with values between 0 and 10,000, increasing values suggesting a higher level of market concentration. The index is formed by summing the squares of individual operator market shares within each market – the functional form has the impact of skewing higher results to market where individual operators have very high market shares.
- We also leverage the Lerner Index as a measure of competition: The Lerner index describes competition intensity as the difference between the price that prevails in the market and the equilibrium price that would result in perfect competition. If we assume homogenous good and constant marginal costs, the EBITDA margin is a valid approximation to the Lerner index of market power.

HHI is based on market shares (by connections), which were sourced from GSMA Intelligence.¹⁴ EBITDA data is also sourced from GSMA Intelligence, which gathers the information from operator-reported data. It is worth noting that our EBITDA dataset comprises just under 2,000 observations during the period of analysis, compared to more than 3000 for HHI. The results are therefore subject to data limitations in terms of what is reported by operators, though the overall sample size is more than sufficient to consider an econometric analysis.

3.5 Consumer pricing

In order to consider the impact of market structure on the full range of outcomes that are valued by consumers, it is important to look at the price of mobile services. However, there are a number of challenges in constructing a price measure that fulfils a representation of consumers' payments as well as one that is consistent over time. Figure 13 sets out the three main ways prices can be measured for mobile services, along with the some of the advantages and disadvantages of each metric.

¹⁴ <https://www.gsmainelligence.com/>

Figure 13: Measures of mobile prices

Price metric	Description	Pros	Cons
Average revenue per user (ARPU)	Divide operator revenues by subscribers or connections	Relatively easy to source data and calculate.	<p>Metric is affected by prices <i>and</i> usage.</p> <p>Does not measure effectively changes to tariffs and plans currently being offered by mobile operators. Can also include other sources of revenue such as handsets and value-added services.</p> <p>ARPU blends all of the customers and associated revenue and is therefore skewed by connections with low activity.</p>
Basket-based pricing	Define a basket of mobile services (e.g. 1GB of data + 500 minutes per month) in order to assess differences in price across countries and time. Basket prices are typically generated by researching the lowest priced package for the basket specified in each time period.	<p>Gives a better indication of what consumers actually pay for mobile services.</p> <p>Can fix baskets to ensure only price changes (and not quantity) are taken into account</p>	<p>Difficult to identify baskets that are representative for majority of consumers.</p> <p>Fixed baskets are not representative over time.</p> <p>Changing baskets over time means price changes are also affected by usage.</p>
Unit-based pricing	Effective price per MB (or other unit such as minutes) which can be drawn from the cheapest basket on a per MB basis, or from average revenue per MB where revenues are disaggregated by operators.	<p>Controls for changes in quantity consumed.</p> <p>Consistent with assessment of investment, which allows for greater capacity and usage of data.</p>	Difficult to estimate as voice, SMS and data are bundled together.

For the period 2011-2018 and for the countries included in the study, the only metric that was available to us to perform pricing analysis at the operator or country level was average (recurring) revenue per user (ARPU). We therefore carry out our empirical analysis using this metric. However, given the shortcomings of ARPU as a measure of prices, the results should be treated with caution. This is an area that would benefit from future research, particularly the development of advanced measures of unit prices that incorporate quality-adjustments.

4. Methodology

Our data consisted of a cross-sectional panel spanning 99 operators across 29 countries and 31 quarters between Q2 2011 and Q4 2018. Our main study variables were the market concentration measures of number of players, HHI and the Lerner Index. We sought to investigate their effects on the four performance measures to get a comprehensive view of the impact of market structure across different aspects of the industry; network quality; network coverage; investment and prices.

Our starting method is a basic cross-sectional OLS panel estimation of our data with the following functional form:

$$(1) \ y_{i,c,t} = \alpha + \gamma_c C_c + \lambda_t T_t + \sum_{i,c,t=1}^{I,C,T} \mu_{ict} X_{ict} + \rho_{ct} Z_{ct} + \varepsilon_{i,c,t}$$

Where:

$y_{i,c,t}$ is a performance or investment outcome of an operator i in country c in quarter t , e.g. download speeds, upload speeds, latencies, coverage or investment

C_c and T_t are a country and time fixed effects – they capture any unobserved variation in consumer outcomes that can be attributed to specific characteristics of each country (e.g geography and topology) and year (e.g. technology upgrades, new handset releases)

X_{ict} is a set of control variables that predict changes in consumer outcomes. These vary for each consumer outcome but generally include aspects such as income per capita, rural population share and spectrum holdings.

Z_{ct} is the market concentration measure – either the number of operators or HHI in country c and quarter t . When using the Lerner Index, we apply this at the operator level (Z_{ict}), as a measure of market power.

Our model is based at the operator level, as opposed to the country level, so that we can maximise the number of observations used, and use the variation between operators within countries to drive results.

Using an operator-level model means that we can use country fixed effects and country-specific trends to control for unobserved factors in individual countries (and over time within those countries). The remaining control variables are:

- GDP per capita: capturing incomes capture the potential differences in demand for mobile services
- Rural population share: sparsely populated countries are harder to provide coverage to than more densely populated countries. In addition, providing capacity to rural areas is harder than for urban areas, due to greater requirements to invest in backhaul. This measure is preferred to population density because of the anomalies of uninhabited land. We note that the drawback of rural population share estimates (from Eurostat) is that each country carries its own definition of rural areas.

- Total country spectrum holdings : spectrum is a key part of the capacity available to operators. While we could include spectrum holdings at the operator level, one of the reasons why operators in more concentrated markets could potentially deliver better network quality or coverage is that spectrum resources are less dispersed between operators. As we want to capture this effect when assessing market structure, we have used total country spectrum holdings by technology (e.g. 4G or 3G or all).

However, it is well acknowledged that market concentration can be affected by market outcomes as much as market outcomes are affected by market concentration. This two-way causality issue can be addressed by using instruments in place of the market concentration variables. Our model for the first stage regression is:

$$(2a) \quad Z_{c,t} = \alpha + \eta_{ct} H_{ct} + \omega_{i,c,t}$$

From which fitted values of Z_{ct} are used in the second stage:

$$(2b) \quad y_{i,c,t} = \alpha + \gamma_c C_c + \lambda_t T_t + \sum_{i,c,t=1}^{I,C,T} \mu_{ict} X_{ict} + \rho_{ct} \tilde{Z}_{ct} + \varepsilon_{i,c,t}$$

Selecting instruments for first-stage model (2a) involves ensuring that any instrument is correlated with Z_{ct} but not with the error term from the second stage regression $\varepsilon_{i,c,t}$. We selected the following instrumental variables:

- For HHI: the transformation of the share of spectrum holdings from the previous generation – i.e. when assessing 4G outcomes, this will be the share of 3G spectrum holdings.¹⁵ As 3G spectrum was typically auctioned in the 2000s, it is unlikely to impact consumer outcomes during the 4G era, especially as 4G services were delivered over different spectrum bands. However, it is very likely to have formed the basis of market concentration going into the 4G era.
- For Lerner Index: the amount of time since the operator launched its first network in the country. The more years since launch, the higher the value of the Lerner index that we would expect, since more time in the market may provide more efficient operations, scale, and knowledge, impacting both operators costs and its product differentiation or substitutability.

When using the number of firms in a market, we do not leverage an instrumental variable approach but instead rely on the OLS specification in equation 1, based on the assumption that the number of operators in a market is exogenous (once country fixed effects and time trends are controlled for). As outlined in Genakos et al (2018), the mobile industry is not a free-entry industry and the number of firms in the mobile market is determined to a significant extent by the availability of spectrum and the award of spectrum licenses, which are unlikely to be determined significantly by mobile investment and

¹⁵ We re-created an index of HHI using 3G spectrum shares instead of market shares and then employed a 2SLS approach using this as an instrument for HHI. It is in effect a replacement of (connections) market share with spectrum share when calculating these indices. For example, HHI, which is the sum of squared (connections) market shares was replaced with the sum of squared spectrum shares.

network quality. Furthermore, the number of operators takes a limited number of values in our analysis (3 or 4). However, by contrast, changes in market shares and profitability within a market (which drive HHI and the Lerner Index) are much more likely to be driven by investment, mobile prices and network quality and may therefore be endogenous.

In order to determine whether results are robust, we also estimated the model using operator fixed effects (instead of country fixed effects). Operator fixed effect models allow us to control for potentially unobserved factors at the operator-level, for example different business strategies, resources, firm structure, size and management. These factors may have some effect on the degree of investment, innovation and/or quality of each operator. It also allows us to check whether the results using country fixed effects are potentially masking the results of struggling operators in concentrated markets. On the other hand, a model with operator fixed effects significantly reduces the amount of variation in the data that the model can exploit. It may also narrow the scope of the analysis too much if the key unobserved variables that impact network quality or investment operate primarily at the country level. We therefore use country-fixed effects when presenting our central estimates and we use operator-fixed effects as a robustness check.

5. Results

5.1 Investment

Table 1 presents the results of the OLS regressions for log capex per operator, which is the metric that has been used as a proxy for innovation and quality in previous studies. We find that more concentrated markets are linked to higher investment levels per operator. There is also some evidence to suggest that the relationship is also non-linear, as the included square term of HHI has a negative and statistically significant coefficient, supporting the “U-shaped” investment and competition relationship that is suggested by economic theory and has also been found in previous studies¹⁶. We find similar results when we use the Lerner Index as a measure of market power, with higher margins associated with greater investment. The relationship between the two is also “U-shaped”.

The results show that other controls have the expected sign, with higher investment linked to higher GDP per capita and more spectrum, though they are not significant.

When we run the analysis at country level, we find that these relationships do not hold, which is also consistent with much of the existing literature (see Annex 1). The results also show there is a positive but statistically insignificant link between the market having 3-players (vs 4 or more players) and investment per operator.

Table 1: Market concentration impact on investment per operator (OLS)

	(1) OLS-FE Log Capex per operator	(2) OLS-FE Log Capex per operator	(3) OLS-FE Log Capex per operator
Share of rural population	-0.377 (0.585)	-0.492 (0.596)	-0.442 (0.506)
GDP per capita	0.775 (0.570)	0.837 (0.531)	0.788 (0.571)
Spectrum holdings	0.000413 (0.000271)	0.000641** (0.000266)	0.000378 (0.000270)
HHI	0.00197*** (0.000580)		
HHI squared	-0.000000231*** (8.32e-08)		
Lerner Index		2.166*** (0.273)	
Lerner Index squared		-0.210*** (0.0240)	
3-player			0.260 (0.158)
Constant	22.75 (28.55)	30.86 (28.55)	29.48 (25.16)
R ²	0.791	0.822	0.790
Number of observations	1821	1731	1821
Number of clusters	28	28	28

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

¹⁶ Hounghonon & Jeanjean, 2017 and 2018; Abate, Castells & Pedros, 2018.

Table 2 presents the results when we look to address the potential endogeneity bias that could arise if investment drives market structure or margins. Based on the IV regressions, the results for HHI become statistically insignificant but the results for the Lerner Index still hold. This suggests that the positive link between concentration and investment only materialises when operators also enjoy higher profit margins.

The results and diagnostics of the first stage regressions are presented in Annex 2 and they suggest that our selected instruments – 3G spectrum share index and the amount of time that an operator has been active in the market – are valid for HHI and the Lerner Index respectively.

We also present in Annex 1 robustness checks of both the OLS and IV models, which show that neither the HHI nor Lerner Index results are statistically significant when we use operator-fixed effects, which is therefore a caveat around the findings.

Table 2: Market concentration impact on investment per operator (IV)

	(1) IV-FE Log Capex per operator	(2) IV-FE Log Capex per operator
Share of rural population	0.0194 (0.658)	-0.162 (1.072)
GDP per capita	0.765 (0.557)	0.896 (0.662)
Spectrum holdings	0.000440 (0.000320)	0.00116*** (0.000438)
HHI	0.00117 (0.000757)	
Lerner Index		10.78** (4.636)
Constant	4.466 (33.65)	11.91 (48.06)
Number of observations	1821	1660
Number of clusters	28	28

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

5.2 Network Quality

While investment can be a useful proxy for operator performance and innovation, it is ultimately an input that impacts the outcomes that are important to consumers. It is therefore preferable to measure these outcomes directly, rather than to rely solely on proxy measures. It is also possible that market structures impact not just the amount of financial investment but also the efficiency per unit of investment, especially in the presence of large fixed and common costs and economies of scale and scope.

Tables 3 presents the results for download speeds using the instrumental variable approach for HHI and the Lerner Index and OLS for the number of operators in the market. In the case of HHI, there was a negative but statistically insignificant effect on network quality. However, as seen in the trend analysis in Section 3, there was a notable divergence in network quality between three- and four-player markets

from 2015, when most operators had reached 90% coverage. This was also around the time when profitability increased in three-player markets relative to four-player markets.

We therefore estimated a variation of our model where we included a '4G 90% coverage' dummy variable (which takes a value of 1 when operators reach 90% population coverage) and interacted it with the market concentration variable. The results are also presented in Table 3. They show that after operators reached 90% 4G coverage, every 1,000 increase in the HHI index drove a 4.4 Mbps increase in overall download speeds, and that this result is statistically significant. The average difference between three and four player markets was approximately 780. Therefore, the results suggest that the average difference between European three and four player markets in speeds was 3.45 Mbps after operators reached 90% 4G coverage. We also ran the regression in column 1 by restricting the sample to observations where operators had reached 90% 4G coverage, as an alternative to the interaction approach. The results are presented in Annex 1 and are consistent with the finding that there is a positive and statistically significant effect of HHI on download speeds.

When looking at the Lerner Index, the results show that, for the period as a whole¹⁷, higher levels of profitability drove higher network quality in terms of download speeds, with a 1 percentage point increase in EBITDA margin driving an increase in download speeds of 0.33Mbps.¹⁸ This suggests that greater profitability may have allowed operators to invest more (as seen in Section 5.1).

When using the number of firms in the market, we find that over the whole period of analysis, download speeds were higher in three-player markets, but this is not statistically significant. However, when we look at the period after operators achieved 90% 4G coverage, as we also did for HHI, the results suggest that the three-player markets had download speeds that were 3.35Mbps higher. This is of a similar magnitude to the calculation using HHI.

Other controls have the expected sign and significance, for example, improved network quality is linked to higher GDP per capita and operators having more spectrum.

Table 3: Market concentration impact on download speeds

	(1) IV-FE Download Speeds	(2) IV-FE Download Speeds	(3) IV-FE Download Speeds	(4) OLS-FE Download Speeds	(5) OLS-FE Download Speeds
Share of rural population	7.171 (9.209)	10.90 (10.96)	12.11 (14.18)	7.702 (9.085)	10.23 (11.41)
GDP per capita (log)	18.06*** (4.092)	14.60*** (3.525)	19.84*** (3.218)	18.01*** (4.206)	14.57*** (3.591)
Spectrum holdings	0.00549* (0.00329)	0.00885** (0.00345)	0.00462 (0.00472)	0.00546 (0.00341)	0.00890** (0.00345)
HHI	-0.00153 (0.00754)	-0.000328 (0.00582)			
HHI (post 90% coverage)		0.00443* (0.00256)			

¹⁷ In the case of the Lerner Index, the econometric results suggested there was no significant difference between the period after operators achieved more than 90% coverage (unlike for HHI and the 3-player analysis).

¹⁸ EBITDA generally takes a value between 0 and 1, so converting into percentage means that we divide the coefficient associated with the Lerner Index by 100 in order to measure the impact of a 1 percentage point increase.

Lerner Index	33.12*** (9.892)				
3-player				0.122 (1.777)	-0.0471 (1.623)
3-player (post 90% coverage)					3.350* (1.809)
Post 90% coverage		-9.100 (7.392)			3.177*** (0.786)
Constant	-470.1 (422.0)	-617.6 (497.9)	-726.7 (654.6)	-499.9 (404.5)	-588.0 (514.1)
R-Squared				0.805	0.817
Number of observations	2961	2961	1911	2961	2961
Number of clusters	29	29	29	29	29

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

In Annex 1, we present the results of alternative specifications to test the robustness of results for download speeds. It shows that both the HHI and three-player regressions are robust to operator fixed effect models.¹⁹ Furthermore, they show that when we control for spectrum at the operator rather than country level, we find positive and statistically significant effects for both the 3-player and HHI variables, as well as the spectrum per operator variable. This means that the amount of spectrum per operator has a significant impact on network quality and, in addition, there remains a network quality ‘premium’ associated with operators in more concentrated markets.

Additionally, we find a positive link between market concentration and other measures of network quality (upload speeds and latency), though most of the results are not statistically significant (see Annex 1).

5.3 4G Coverage

When we consider the impact of market structure on 4G coverage, table 4 shows that there is some evidence to suggest a link between higher profit margins and greater 4G coverage, based on the IV regression for the Lerner Index. However, the results for the HHI and 3-player market models are statistically insignificant.

Other controls have the expected sign and significance, for example, higher 4G coverage is linked to higher GDP per capita and to operators having more 4G spectrum and having held spectrum for longer.

Table 4: Market concentration impact on 4G network coverage

	(1) IV-FE 4G coverage	(2) IV-FE 4G coverage	(3) OLS-FE 4G coverage
Share of rural population	-0.151 (0.114)	-0.133 (0.198)	-0.161 (0.117)
GDP per capita (log)	0.147*** (0.0342)	0.250** (0.101)	0.146*** (0.0353)

¹⁹ When using operator fixed effects, our instrument for the Lerner Index ceases to be valid (see Annex 2) so we do not present those results.

Spectrum holdings (4G)	0.000419*** (0.0000992)	0.000491*** (0.000123)	0.000427*** (0.000104)
2-4 years since acquiring 4G spectrum	0.175*** (0.0199)	0.204*** (0.0354)	0.175*** (0.0205)
4 years plus since acquiring 4G spectrum	0.277*** (0.0264)	0.323*** (0.0476)	0.277*** (0.0275)
HHI	0.0000490 (0.0000850)		
Lerner Index		1.758* (1.017)	
3-player			-0.00726 (0.0473)
Constant	5.545 (5.273)	3.165 (8.934)	6.215 (5.350)
R ²			0.770
Number of observations	2248	1383	2248
Number of clusters	29	28	29

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

5.4 ARPU

Table 5 presents the IV results for HHI and the OLS results for the 3-player market measure for ARPU.²⁰ Neither of the models suggest a statistically significant relationship between market structure and ARPU. However, given the limitations of ARPU as a measure of consumer prices, these results should be treated with caution.

Table 5: Market concentration impact on ARPU

	(1) IV-FE Log ARPU	(2) OLS-FE Log ARPU
Share of rural population	0.107 (0.177)	0.110 (0.178)
GDP per capita (log)	0.307*** (0.0521)	0.306*** (0.0526)
Spectrum holdings	-0.000230*** (0.0000639)	-0.000234*** (0.0000664)
HHI	-0.0000106 (0.000107)	
3-player		0.0275 (0.0299)
Constant	-4.518 (8.199)	-4.750 (8.185)
R ²		0.877
Number of observations	2918	2918
Number of clusters	29	29

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

²⁰ We do not present the results using the Lerner Index as this is approximated using EBITDA and so both the dependent and independent variable of interest incorporate operator revenues in their calculations.

6. Conclusions

The 4G era was an expansive one for the European mobile industry. By 2016, 90% of European consumers were covered by 4G networks. Speeds improved significantly and latency decreased, leading to a much improved consumer experience. The average price per MB dropped significantly, as mobile data became cheaper and users consumed ever-increasing volumes of data.

The key finding from the analysis in this study is that European mobile users in more concentrated markets benefitted the most from higher network quality, particularly with regard to download speeds. By the end of 2018, three-player markets were outperforming four-player markets by 4.5Mbps. Our econometric analysis shows that over half that difference, 3.3-3.5Mbps, can be attributed to the role of the market structure in three-player markets generating greater speeds, once other factors are accounted for.

It is notable, however, that this effect only manifests in the second half of the period, after 2015. To understand this, it is important to consider two factors that are likely to have been at play.

First, operators in three-player markets enjoyed economies of scale that allowed them to optimise their use of assets, such as spectrum. Dispersion of these among a greater number of players can result in a less efficient use of such resources, which can translate into lower network performance, to the detriment of users. From 2016, when the majority of European countries had assigned spectrum in the 800 and 2600MHz bands (and some re-farming of 1800MHz), operators in three-player markets had on average 14% more 4G spectrum than operators in four-player markets.²¹ The econometric results also support the hypothesis that operators with more spectrum are able to achieve greater levels of network quality.

Second, we find strong evidence of investment being greater in more concentrated markets. The fact that operators in 3-player markets had higher profit margins from 2015 onwards means that their capacity and ability to invest in newer and faster technologies (such as LTE Advanced) also increased. This is supported by our econometric analysis, which shows that operators with higher profit margins invested more and achieved better levels of network quality.

It is important for governments, regulators and competition authorities to consider the lessons this study provides, including the relative advantages of more concentrated market structures in terms of network quality. While every market is unique, regulators that are aiming to increase the number of players or considering preventing the reduction in the number of players (e.g. merger control) should reflect carefully on the likely impact this could have on network performance and the consumer experience.

Going forward, while this study has robustly considered the impact of mobile market structure on network coverage, quality and investment, due to data limitations it cannot draw conclusive findings when it comes to considering the effect on consumer prices. Given the conflicting findings in the existing literature on the impact of market consolidation and prices, this area would benefit from the development

²¹ Source: GSMA Intelligence. At the end of 2018, operators in three-player markets had an average of more than 103MHz of spectrum that could be used for 4G compared to 91MHz in four-player markets.

of more sophisticated measures of consumer prices that incorporate both volume- and quality-adjustments.

Annex 1: Robustness checks

In this annex, we present the results of additional models for investment and download speeds, in particular those where we found significant results in our ‘base’ models. This is to check whether our findings are robust to alternative specifications and assumptions. We also present the results of our main models for upload speeds and latencies.

Investment

Table A1 presents the results of the OLS models for the three measures of market concentration on capex at the country level. None of the results are statistically significant, suggesting no strong link between market structure (either based on the number of players or on HHI or market power) and investment at the country level. This is consistent with previous literature on the subject.

Table A1: Market concentration impact on investment per country (OLS)

	(1) OLS-FE Log Capex by country	(2) OLS-FE Log Capex by country	(3) OLS-FE Log Capex by country
Share of rural population	-0.265 (0.414)	-0.275 (0.431)	-0.279 (0.404)
GDP per capita	0.327 (0.264)	0.362 (0.276)	0.328 (0.265)
Spectrum holdings	0.000657*** (0.000165)	0.000650*** (0.000169)	0.000647*** (0.000170)
HHI	0.000744 (0.000786)		
HHI squared	-0.0000000989 (0.000000120)		
Lerner Index		-0.0913 (0.0616)	
Lerner Index squared		0.00495 (0.0208)	
3-player			0.0835 (0.0680)
Constant	25.51 (19.25)	27.12 (20.08)	27.47 (18.81)
R ²	0.972	0.969	0.972
Number of observations	867	845	867
Number of clusters	28	28	28

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

Table A2 presents the results of the OLS and IV models for HHI and the Lerner Index at the operator level using operator fixed effects (instead of country fixed effects). The results show that while there remains a positive association between market concentration and investment, it becomes statistically insignificant when we use operator fixed effects (though in the case of the IV regression, the Lerner index model should be treated with significant caution as the diagnostics in Annex 2 show that our instrument works less well when operator fixed effects are used).

Table A2: Robustness checks for market concentration and market power impact on download speeds

	(1) Country fixed effects (OLS)	(2) Operator fixed effects (OLS)	(3) Country fixed effects (IV)	(4) Operator fixed effects (IV)
HHI	0.00197*** (0.000580)	0.000611 (0.00116)	0.00117 (0.000757)	0.000625 (0.000822)
HHI squared	-0.000000231*** (8.32e-08)	-2.52e-08 (0.000000170)		
Lerner Index	2.166*** (0.273)	0.174 (0.761)	10.78** (4.636)	17.26 (36.37)
Lerner Index Squared	-0.210*** (0.0240)	-0.0235 (0.0702)		

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends and the same control variables as in Section 5.

Download speeds

Table A3 shows how the results for download speeds change when we adjust the IV regressions based on market concentration (HHI). When we restrict the sample to observations where operators had at least 90% 4G coverage (column 2), instead of using an interaction approach, we find that our result holds and is in fact even stronger. Column 3 shows that the base result is robust to operator fixed effects. Column 4 also shows that when we control for spectrum at the operator rather than country level, we find positive and statistically significant effects for both the HHI and spectrum variables. This means that the amount of spectrum per operator has a significant impact on network quality and, in addition, there remains a network quality ‘premium’ associated with more concentrated markets.

We do not present robustness checks for the IV regression based on the Lerner Index using operator fixed effects because the results in Annex 2 show that when an operator fixed-effect model is used, the amount of time since network launch is not a valid instrument for the Lerner Index.

Table A3: Robustness checks for market concentration impact on download speeds

	(1) Base result	(2) Restrict sample to post 90% 4G coverage	(3) Operator fixed effects	(4) Spectrum per operator
HHI (post 90% coverage)	0.00443* (0.00256)	0.09632** (0.04085)	0.00825*** (0.00274)	0.00465* (0.0025)
Spectrum per operator				0.035*** (0.009)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends and the same control variables as in Section 5.

Table A4 presents the results of the OLS model for the number of players in the market using alternative specifications.²² Column 2 shows that the finding that three-player markets had higher download speeds after operators achieved 90% coverage is robust to operator fixed effects. Column 3 also shows that

²² We do not present the results of the regression that restricts the sample to observations where operators have at least 90% 4G coverage because there is insufficient variation within countries in the number of players in the market (i.e. when we restrict the sample to post-90% 4G coverage observations, almost all countries stayed as 3 or 4 player markets).

when we control for spectrum at the operator rather than country level, we find positive and statistically significant effects for both the 3-player and spectrum variables.

When we add Sweden and Denmark to the three-player group (where there is core network sharing between operators) in Column 4, we find that the three-player impact becomes statistically insignificant. The same result is observed when we add markets with RAN sharing (United Kingdom, Romania, Poland) to the group.²³ This suggests that three-player markets drive better network quality than 4-player markets with network sharing, even those with deeper levels of sharing. However, given the lack of variation in data, it was not possible to conclusively test whether different forms of network sharing drive different impacts on network quality. This is an area where further research is needed.

Table A4: Robustness checks for Three-player market impact on download speeds

	(1) Base result	(2) Operator fixed effects	(3) Spectrum per operator	(4) Three-player with core sharing	(5) Three-player + all active shares
3-player (post 90% coverage)	3.350* (1.809)	4.198** (1.544)	3.950** (1.739)	2.287 (1.685)	-1.704 (2.417)
Spectrum per operator			0.035*** (0.009)		

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends and the same control variables as in Section 5.

Upload Speeds

Table A5 presents the results for upload speeds using the instrumental variable approach for HHI and the Lerner Index and OLS for the number of operators in the market. While there is evidence to suggest that higher profit margins drove greater upload speeds, there is no statistically significant relationship between HHI or the number of players in the market and upload speeds.

²³ However, when we include markets with active RAN sharing in the three-player group, the number of countries in the four-player group becomes significantly small by this point – only Slovenia, Slovakia, Spain, France and the Netherlands remain. Therefore, this sensitivity analysis and result should be treated with caution.

Table A5: Market concentration impact on upload speeds

	(1) IV-FE Upload Speeds	(2) IV-FE Upload Speeds	(3) IV-FE Upload Speeds	(4) OLS-FE Upload Speeds	(5) OLS-FE Upload Speeds
Share of rural population	-1.414 (2.227)	-0.565 (2.409)	-0.160 (2.031)	-0.532 (1.872)	0.260 (2.072)
GDP per capita (log)	6.704*** (1.550)	5.574*** (1.430)	6.994*** (0.972)	6.614*** (1.559)	5.518*** (1.437)
Spectrum holdings	0.00394*** (0.00118)	0.00513*** (0.00122)	0.00381*** (0.00135)	0.00386*** (0.00113)	0.00496*** (0.00113)
HHI	-0.00254 (0.00271)	-0.00249 (0.00259)			
HHI (post 90% coverage)		0.000217 (0.000902)			
Lerner Index			9.415*** (3.109)		
3-player				0.429 (0.391)	0.435 (0.332)
3-player (post 90% coverage)					0.782 (0.564)
Post 90% coverage		0.953 (2.789)			1.165** (0.425)
Constant	18.35 (100.7)	-11.67 (108.4)	-54.16 (92.64)	-31.33 (77.45)	-58.88 (87.66)
R-Squared				0.793	0.802
Number of observations	2961	2961	1911	2961	2961
Number of clusters	29	29	29	29	29

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

Latency

Table A6 presents the results for latencies using the instrumental variable approach for HHI and the Lerner Index and OLS for the number of operators in the market. None of the results suggest there is a statistically significant relationship between market structure or concentration and latencies. This is not an unexpected result because operators exert less control over latency than over other network quality metrics such as speeds. To some extent, latency can be controlled by the densification of base stations and an increase in capacity to avoid queuing of data packets at network switches. However, latency also depends on the location of the customer and the server from which the customer is demanding data.

Table A6: Market concentration impact on latency

	(1) IV-FE Latency	(2) IV-FE Latency	(3) IV-FE Latency	(4) OLS-FE Latency	(5) OLS-FE Latency
Share of rural population	49.26 (41.93)	43.57 (43.04)	74.09 (58.98)	31.78 (39.55)	28.39 (40.75)
GDP per capita (log)	-50.35*** (16.54)	-45.32*** (15.64)	-67.67*** (23.63)	-48.33*** (15.15)	-43.34*** (14.46)
Spectrum holdings	-0.179*** (0.0235)	-0.184*** (0.0236)	-0.174*** (0.0278)	-0.177*** (0.0218)	-0.182*** (0.0227)
HHI	0.0502 (0.0685)	0.0482 (0.0669)			
HHI (post 90% coverage)		-0.00731 (0.0153)			
Lerner Index			-62.48 (97.09)		
3-player				-15.08 (11.17)	-16.14 (12.09)
3-player (post 90% coverage)					1.381 (10.65)
Post 90% coverage		16.00 (50.84)			-7.971 (9.455)
Constant	-1728.4 (2041.6)	-1501.1 (2098.7)	-2497.0 (2668.2)	-737.9 (1805.8)	-621.2 (1874.0)
R-Squared				0.735	0.736
Number of observations	2961	2961	1911	2961	2961
Number of clusters	29	29	29	29	29

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Country-clustered standard errors in parentheses

Includes country fixed effects and country-specific year trends

Annex 2: First stage IV outputs for market concentration analysis

Table A7 presents the results and diagnostics of the first stage regressions on HHI (where the 3G spectrum share index is used as an instrument) and the Lerner Index (where the time since the operator's first network launch is used as an instrument).

The results show that in models with country-fixed effects, both instruments are statistically significant and operate in the expected direction, i.e. more concentrated 3G spectrum shares are linked to a higher HHI in the 4G era and operators that have been active in a market for longer have a higher Lerner Index value. The F-statistic and the p-values of the Sanderson-Windmeijer statistics for under-identification and weak identification also indicate that both instruments are valid.

When we use operator fixed effects, the instrument for HHI remains valid but the diagnostics suggest that time since network launch becomes a much less valid instrument for the Lerner Index, as the coefficient becomes statistically insignificant and the diagnostics mean that we cannot reject the null hypothesis that the instrument is weakly identified.

Table A7: First stage OLS regressions for HHI and Lerner Index

	(1) HHI	(2) HHI	(3) Lerner Index	(4) Lerner Index
Share of rural population	-382.7** (169.3)	-381.0** (167.2)	-0.00663 (0.0608)	0.00497 (0.0473)
GDP per capita (log)	36.42 (70.54)	35.90 (70.10)	-0.0474 (0.0434)	-0.0593 (0.0620)
Spectrum holdings	-0.0362 (0.120)	-0.0381 (0.119)	-0.0000550 (0.0000353)	-0.0000470 (0.0000337)
3G Spectrum Share Index	0.811*** (0.240)	0.812*** (0.238)		
Time since network launch			0.00243** (0.000948)	0.00321 (0.00371)
Constant	18279.4** (7744.6)	10971.5** (4596.0)	0.967 (2.578)	0.501 (1.209)
R ²	0.966	0.700	0.486	0.222
Number of observations	2961	2961	1911	1911
Fixed effect	Country	Operator	Country	Operator
First-stage F-test ²⁴	11.44 (0.00)	11.24 (0.00)	6.555 (0.016)	0.716 (0.404)
Under identification p-value ²⁵	0.001	0.000	0.008	0.787
Weak identification p-value ²⁶	0.002	0.002	0.016	0.716
Endogeneity p-value ²⁷	0.839	0.873	0.001	0.000

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

²⁴ Reports the F statistic for joint significance and the associated p-value. If the F statistic is not significant, then the additional instruments have no significant explanatory power. F statistic greater than 10 is often used to suggest instruments are sufficiently strong.

²⁵ Reports the p-value of the Sanderson-Windmeijer statistic. Null hypothesis is that the model is underidentified.

²⁶ Reports the p-value of the Sanderson-Windmeijer statistic. Null hypothesis is that the model is weakly identified.

²⁷ Reports the p-value of the endogeneity test (regression-based test). Null hypothesis is that the endogenous regressors are in fact exogenous.

Annex 3: References

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