GSMA Intelligence

Global Spectrum Pricing

Methodology

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1. Benchmarking of unit prices and spectrum cost-to-revenue ratio

Benchmarking

GSMA Intelligence performed benchmarking analysis of unit spectrum prices over time based on a licence-level dataset of more than 5,000 individual spectrum licences. For each licence, the dataset includes information on the frequency band, bandwidth (MHz), licence start and end date, duration and applicable geographic area (typically a country, but also a region for licences in some countries). From the data, we calculate unit prices for different band and year combinations using benchmark formulas.

We relied on two different definitions of unit prices:

- Spectrum cost per unit of population (2023 $PPP/MHz/year/population, adjusted for weighted cost of capital). In the case of regional (sub-national) licences, the benchmark is based on the population covered by the licence.
- Spectrum cost per unit of revenue ($/MHz/year/$ million of mobile market recurring revenue at the time of assignment, adjusted for weighted cost of capital). In the case of regional licences, the market revenue is weighted by the population covered by the licence as a percentage of the total population.

Data sources are shown in Table 1. Licence-level data used in the benchmarking covers assignments from 2012 or later.

Table 1 Data sources used in the benchmarking of spectrum prices

Licence-level data	Period	Source
Individual licence start and end dates, bandwidth, frequency band, prices.	2012–2024	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025), supplemented with data collected from operators on annual licence fees.
Market data	**Period**	**Source**
Mobile market recurring revenue	2012–2024	GSMA Intelligence, 2024
Population	2012–2024	IMF World Economic Outlook, 2024
Currency exchange rates	2012–2024	IMF World Economic Outlook, 2024
Weighted average cost of capital	2012–2024	GSMA Intelligence estimates based on equity risk premium data by Damodaran (2024), average gearing ratio estimates for the telecoms sector by Damodaran (2024) and the risk-free rate proxy based on the US 3-Month Treasury Bill Secondary Market

	Rate data from the Federal Reserve Bank of St. Louis.

Source: GSMA Intelligence

Adjustment for the weighted average cost of capital (WACC) reflects the time value of money when operators are required to pay upfront for a licence with a given duration. The WACC adjustment amortises the cost of a licence over its duration, taking into account the cost of capital required to make an upfront payment (or a given schedule of instalments).

The WACC-adjusted annualised payment is calculated using a formula converting the present value of a lump-sum payment into an equivalent annuity with payments over the duration of the licence.

Equation 1 Adjustment of upfront cost based on the cost of capital

$$WACC\ adjusted\ anualised\ licence\ cost = \frac{Upfront\ cost}{\dfrac{1-\left(\dfrac{1}{1+WACC\ rate}\right)^{Duration\ in\ years}}{WACC\ rate}}$$

Hence, the present value (discounted value) of the annualised cost is equal to the present value of the lump sum.

Spectrum cost-to-revenue ratio

We rely on the spectrum cost-to-revenue ratio as a measure of the total cost of spectrum from all active licences owned by an operator. For each operator, we calculate the spectrum cost-to-revenue ratio as specified in Equation 2.

Equation 2 Formula of spectrum cost-to-revenue ratio

$$Spectrum\ cost\ to\ recurring\ revenue\ ratio = \frac{WACC\ adjusted\ annual\ upfront\ cost\ of\ all\ active\ licences\ + Annual\ spectrum\ fees}{Annual\ recurring\ revenue}$$

The WACC-adjusted annualised spectrum cost for each active licence is calculated as outlined earlier in *Benchmarking*. The cost of licences that started or expired during a particular year is attributed in proportion to the number of days the licence remained active in a given year. For example, if a licence ended on the 100th day of the year, only 100/365 of the annualised cost of the licence was attributed to that year.

Annual recurring revenue data has been sourced from the GSMA Intelligence database.[1] Recurring revenue is defined as revenue from mobile subscriptions, excluding other streams such as sales of devices.

[1] GSMA Intelligence

Table 2 Data sources used in the calculation of spectrum cost-to-revenue ratio

Licence-level data	**Period**	**Source**
Cost of spectrum ($)	2014–2024	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025), supplemented with data collected from operators on annual licence fees. Data includes licences dating back to the 1990s, some of which remained active as late as 2014 and contributed to the cost of spectrum in the period examined.
Market data	**Period**	**Source**
Mobile market recurring revenue	2012–2024	GSMA Intelligence, 2024
Population	2012–2024	IMF World Economic Outlook, 2024
Currency exchange rates	2012–2024	IMF World Economic Outlook, 2024
Weighted average cost of capital	2012–2024	GSMA Intelligence estimates based on equity risk premium data by Damodaran (2024), average gearing ratio estimates for the telecoms sector by Damodaran (2024) and the risk-free rate proxy based on the US 3-Month Treasury Bill Secondary Market Rate data from the Federal Reserve Bank of St. Louis.

Source: GSMA Intelligence

2. Analysis of impacts on consumer outcomes

Dataset

For the estimation of impacts, we construct an operator-level dataset with quarterly frequency of observations. Quarterly data on total spectrum holdings (MHz held by each operator) and the aggregate cost are constructed from data on individual spectrum licences discussed in the preceding chapter. Licence-level data was primarily sourced from the GSMA Intelligence Spectrum Navigator database, which is collected from public announcements of assignments. This was supplemented with the validation and collection of additional data from operators, including data on licences and prices paid, as well as annual spectrum fees paid. In some instances, operators provided combined spectrum cost data, rather than individual licence data. We amortised these over the expected licence duration based on known assignments from the same country. Attribution of spectrum cost to each quarter is based on licences that were active for the whole or part of the quarter. In the case of licences that started or expired during a quarter in question, we have attributed a proportion of quarterly cost based on how much of the quarter the licences remained active for.

We obtain the total spectrum held by an operator in a given quarter by summing the amount of MHz across all active licences below the 7 GHz frequency range. We excluded mmWave spectrum as it is deployed in more limited areas and generally involves large amounts of MHz, which would distort comparisons. Where a licence starts or expires during the given quarter, the MHz amount is weighted according to how much of the quarter the licence remained active for.

The availability of spectrum and spectrum cost data was a key determinant in our decision to include each observation in the analysis, as described in the section on the limitations of the dataset.

Data on average download speeds, upload speeds and latencies experienced by consumers is obtained from the Ookla Speedtest Intelligence database.[2] Each network quality metric is crowdsourced using Ookla's mobile app and aggregated by operator. To obtain weighted speeds across all network generations, the mean speeds for each mobile network generation are weighted using the number of connections for each network generation in each country. The number of connections for each network generation is sourced from the GSMA Intelligence database.

Data on 4G and 5G network coverage is sourced from GSMA Intelligence. This is expressed as the proportion of the population resident in an area where 4G or 5G networks are available (i.e. coverage by population rather than by geographic area). The data is gathered from publicly available reports from operators and regulators. Where coverage is not reported in each quarter, data is estimated by GSMA Intelligence.

[2] Speedtest Intelligence, 2024, Ookla

As well as the key policy and outcome variables, we source data on control variables. We use IMF data on GDP per capita, measured in US dollars, adjusted for purchasing power parity (PPP). We use the same sources for inflation and PPP adjustment series (IMF WEO).

The sources of data used in the estimation are listed in Table 3.

Table 3 Data sources used in building the estimation dataset

Variable	Period	Source
Spectrum cost ($)	Q1 2014 – Q4 2023	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025), supplemented with data collected from operators on annual licence fees.
Amount of IMT spectrum assigned to public mobile networks	Q1 2014 – Q4 2023	Constructed from licence-level from GSMA Intelligence Spectrum Navigator database (January 2025), supplemented with data collected from operators on annual licence fees.
Crowdsourced data on download speeds (Mbps), upload speeds (Mbps) and latencies (ms)	Q1 2014 – Q4 2023	Ookla Speedtest Intelligence, 2023
Operators' recurring revenue ($)	Q1 2014 – Q4 2023	GSMA Intelligence estimates, 2023
Average revenue per subscriber	Q1 2014 – Q4 2023	GSMA Intelligence estimates, 2023
Number of mobile connections	Q1 2014 – Q4 2023	GSMA Intelligence estimates, 2023
Weighted average cost of capital (%)	Q1 2014 – Q4 2023	GSMA Intelligence estimates based on equity risk premium data by Damodaran (2024), average gearing ratio estimates for the telecoms sector by Damodaran (2024) and the risk-free rate proxy based on the US 3-Month Treasury Bill Secondary Market Rate data from the Federal Reserve Bank of St. Louis.
Control variable	**Period**	**Source**
Mobile sector concentration (Herfindal-Hirschmann Index)	Q1 2014 – Q4 2023	GSMA Intelligence estimates, 2024
GDP per capita ($, constant prices)	Q1 2014 – Q4 2023	IMF World Economic Outlook, 2024 Quarterly series generated by linear interpolation
Share of rural population (%)	Q1 2014 – Q4 2023	World Bank, 2024 Quarterly series generated by linear interpolation
Instrumental variable	**Period**	**Source**

General government debt maturing in 12 months (% of GDP)	Q1 2014 – Q4 2023	World Bank, 2024
General government primary balance (% of GDP)	Q1 2014 – Q4 2023	IMF World Economic Outlook, 2024 Quarterly series generated by linear interpolation
Share of auction-based active assignments in the total number of active assignments, operator-level (%)	Q1 2014 – Q4 2023	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025)
Share of auction-based active assignments where reserve prices were binding, operator-level (%)	Q1 2014 – Q4 2023	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025)
Regional average spectrum cost to recurring revenue ratio	Q1 2014 – Q4 2023	Constructed from licence-level data from GSMA Intelligence Spectrum Navigator database (January 2025)

Source: GSMA Intelligence

Limitations of the dataset

Despite efforts to collect fully comprehensive data on spectrum holdings and their cost, the data may be incomplete for a particular operator and for a particular period.

In some instances, missing data on particular licences means it will not be reflected in the calculation of the total amount of spectrum available to an operator and the cost. In other instances, the licence information may be available, but pricing data missing. Hence, its cost will not be reflected in the estimated spectrum cost metrics (cost-to-revenue ratio and cost per connection).

To perform analysis only on operators where we deem spectrum data to be sufficiently complete, we rely on consistently applied inclusion criteria. We exclude observations where in a given quarter an operator had fewer than 50 MHz of active spectrum licences in bands below 7 GHz. This ensures we exclude operators where a large share of licence data could be missing. Typically, most operators since 2014 would have owned more than 50 MHz of spectrum, so an estimate of below 50 MHz indicates a strong probability of missing licence data. We rely on an additional completeness criteria regarding pricing data. We only include the observations where price data was available for at least 60% of known active licence bandwidth owned by an operator. We do not impute cost where pricing data is missing, as it could also mean that a licence was awarded at no cost. The data available to us did not distinguish between such cases.

Additionally, where supplied by operators or based on a known tariff, the cost of spectrum includes annual fees. However, in some instances the data could be missing or exclude certain fees we had no data on. To ensure consistency, we applied the same definition of spectrum fees. We include annual fees charged on the basis of active licences but exclude fees not directly related to spectrum licences, such as universal service fund contributions or base station inspection fees.

While it has not been possible to obtain complete spectrum data, there is no indication that any of the evaluated outcome measures could be related to the degree to which spectrum data is missing. While it is possible that missing licence data could lead to underestimating the amount of spectrum and its total cost, this will not lead to a bias in the estimated impact parameters because the degree of data missingness is in no obvious way correlated to consumer outcomes of interest, such as network coverage, speeds and latency.

Econometric approach

We relied on statistical analysis to measure the relationship between spectrum cost and consumer outcomes. We empirically examine a set of hypotheses on the impact of spectrum cost and spectrum availability:

- the impact of spectrum cost and spectrum availability on network coverage (4G and 5G)
- the impact of spectrum cost and spectrum availability on network speeds (connection-weighted average speeds across all generations)
- the impact of spectrum cost and spectrum availability on latencies (connection-weighted average latency across all generations).

These cause-and-effect relationships are not directly observable because of various confounding factors and hypothetical bidirectional relationships. This can be exemplified by examining the observed relationship between spectrum cost and consumer outcomes, which is an outcome of the following:

- The actual effect of spectrum cost on consumer outcomes, such as network coverage and network speeds. By capturing and extracting the economic surplus and directing it towards the state, high cost of spectrum can in the long run diminish the commercial viability of certain projects and lead to lower investment and scaled-down deployment of networks.
- The effect of confounders. For example, operators in highly competitive markets can see elevated spectrum cost due to competition to secure access to it. Because of the level of competition, they could also adjust their network deployment strategies. Another confounding effect could stem from the share of rural population. A higher share of rural population can reduce demand and cost of spectrum for operators and, at the same time, limit the viability of network deployment where there is insufficient population to make it commercially viable.
- The effect of time trends. This can occur because as new technologies emerge and improve the quality of networks, there is a general trend of improving consumer outcomes. Concurrently, policymakers in multiple countries have been making more spectrum available, which has increased its availability and combined cost.
- The reverse causal effect, where consumer outcomes such as coverage and network quality affect regulators' approach to spectrum pricing or affect operators' bidding strategies in the case of auctions.

This set of simultaneous relationships can lead to endogeneity bias if relying on inappropriate statistical techniques. This means, for example, that the magnitude of the estimated parameter in univariate models or in multivariate pooled or cross-sectional statistical models is a net result of all factors, rather than a measure of the policy effect alone. We therefore rely on appropriate statistical methods and a set of control variables to remove the influence of confounding effects.

For each tested hypothesis, we use tailored statistical approaches described in the following sections.

To address the effect of observed confounders and time trends, we rely on control variables in the estimated equations to eliminate their effect. We include variables such as GDP per capita, share of rural population, market concentration Herfindahl–Hirschman index, and indicator variables for each year between 2014 and 2023.

To address the effect of various potential unobserved confounders linked to the country of operation, we rely on fixed effects models, which eliminate sources of variation in both the dependent and policy variables that are specific to each country of operation and that remained constant over the examined period, such as geography, climate, regulatory regime and others.

Other unobserved or hard-to-measure confounders can jointly determine spectrum prices and consumer outcomes. For example, market revenue opportunity or consumer readiness and expenditure are drivers of spectrum value because they increase the potential revenue opportunity for an operator. At the same time, consumer expenditure on mobile determines deployment strategy. As expenditure on mobile increases, network deployment becomes commercially viable in additional areas, leading to increased coverage, for example.

To address this potential source of omitted variable bias, we measure spectrum cost as a proportion of recurring revenue. Standardising spectrum cost by market revenues eliminates the source in variation of spectrum cost arising from commercial considerations. For example, identical spectrum licences can have the same price in two similar-sized countries, but this can represent 5% of revenues for an operator in country A and 1% of revenues for an operator in country B. From this comparison, spectrum is less affordable in country B when standardised by the size of potential revenue opportunity.

There is no obvious reason why improved (or worse) consumer outcomes for each operator would have a direct negative (or positive) impact on the cost of spectrum relative to revenues. However, these two could be simultaneously determined by another factor. For example, operators that underestimated the quality of service demanded by consumers and provided scaled-down deployments may have seen a reduction in their market share and revenues. In such instances, one could observe worse consumer outcomes, alongside an elevated spectrum cost-to-revenue ratio. However, it is unlikely that this would have been a persistent pattern. Some operators could underestimate the optimal service quality for a given market, leading to sub-optimal consumer outcomes and elevated spectrum cost-to-revenue ratio. Other operators can make the opposite error and overestimate the optimal service quality, still leading to an elevated spectrum cost-to-revenue ratio as a result of lost revenue.

In terms of measuring the causal relationship between spectrum amount and consumer outcomes, we do not identify a plausible reason for a reverse effect either. Consumer outcomes should not directly affect how much spectrum is made available by the regulator to operators. However, it is possible that regulators can set the policy endogenously – for example, by assigning additional spectrum in response to underperformance in terms of coverage or network speeds. This source of bidirectional relationship is in part addressed by reliance on two-way fixed effects eliminating the country-specific and time-specific effects.

To ensure robustness, we perform the same analysis relying on an alternative definition of spectrum cost, expressing it in terms of ongoing cost per connection (annualised cost of active licences in 2023 $PPP per connection). This measure takes into account the cost of all active spectrum licences and standardises the cost by number of active connections held by an operator. It provides an alternative definition of spectrum cost. However, this metric may be more prone to simultaneity, as both the cost of spectrum per connection and market outcomes may be driven by consumer behaviour and expectations. For example, operators in markets where consumers demand high-quality service and where the revenue per user is high will be ready to pay more for spectrum in per-connection terms and may upscale the deployment to meet the needs of demanding, high-spend consumers.

Hence, the cost per connection metric and the widely used benchmarking metrics, such as $PPP/MHz/year/population, do not fully standardise by the size of potential commercial opportunity. Where adoption of mobile or spend on mobile services is relatively lower, both spectrum cost per connection or per MHz/year/population and outcomes such as coverage and speeds can be jointly determined by these factors.

To address these sources of potential endogeneity, we rely on two-stage estimation and instrumental variables. Instrumenting the policy variables can help exogenise spectrum cost from a potential simultaneity or a reverse causal relationship. In this case, instrumental variables of interest should affect policy choices with respect to pricing but should not have a direct effect on consumer outcomes. We rely on the following instrument candidates for the cost of spectrum:

(i) Central government debt maturing in 12 months or less (as a share of GDP). Maturing short-term debt requires repayment of the principal amount. Governments may seek to raise these funds by maximising revenue from the sale of spectrum. Previous research has found that developing countries with high levels of public indebtedness tend to have higher spectrum prices (though the correlation is not as strong in developed countries).[3] Hence, it is plausible that governments can use spectrum assignments to increase public sector revenues.

(ii) Central government primary balance (as a share of GDP). Similar to short-term debt maturing, governments can try to elevate spectrum cost in order to reduce the primary budget deficit. Many countries rely on fiscal rules that limit the maximum primary deficits that can be approved in the national budget. Additional revenue from the sale of spectrum can therefore be an appealing option for governments to raise additional revenue to cover the deficit. At the same time, the primary balance on general government finances does not have a direct effect on consumer outcomes such as network coverage and quality.

(iii) A continuous variable expressing the percentage of active licences awarded via auctions in the total number of active licences held by an operator. Reliance on auctions rather than administrative process can potentially influence spectrum prices because the mechanism of bidding can potentially elevate prices. Auctions allow the market to determine the price (subject to format and design decisions). However, there is no plausible direct link between the method of assignment and consumer outcomes.

[3] Spectrum pricing in developing countries Evidence to support better and more affordable mobile services, GSMA Intelligence, 2018

(iv) Percentage of active licences sold at reserve prices. Reserve prices can increase spectrum cost for a particular licence because the price paid is based on the reserve price selected by a regulator. This is in contrast to outcomes when bidding occurs, as in second-price auctions the price paid by an operator will be based on the second highest bid. As no bidding occurred when spectrum is sold at reserve prices, the second highest bid would have been lower than the reserve price. Hence, the reserve price increased the final price paid by the winner. This instrument does not invalidate the exclusion restriction because reserve prices do not directly affect consumer outcomes.

(v) Average spectrum cost-to-revenue ratio in the surrounding region. The rationale for this instrument is that regulators often use spectrum prices in surrounding countries or countries in the same region as benchmarks to inform their own reserve prices or the price of spectrum itself. However, pricing of spectrum in neighbouring countries should not affect consumer outcomes in a particular country. For multinational operators with operations in neighbouring countries, we would not expect the cost to matter because each operation is treated as a separate entity.

Econometric models

To estimate the impacts of spectrum cost and spectrum availability on various consumer outcomes, we rely on two-way fixed-effects models. Fixed-effects models are advantageous in this context as they can exploit variation in policy and outcomes within each country, rather than making inferences based on cross-country comparisons. They eliminate the influence of unobservable confounding factors that are specific to each country and could otherwise bias the estimate.

Depending on the modelled variable, we model its levels or its logarithm as a linear projection of explanatory variables (Equation 3). The specified equation denotes the outcome variable for operator *i* in quarter *t* as y_{it} as a function of the spectrum cost faced by the operator in a given quarter (C_{it}) and the respective parameter γ, the amount of spectrum owned by an operator in a given quarter (S_{it}) and the respective parameter σ and a vector of control variables $\boldsymbol{X}'_{it}$ and their respective coefficients $\boldsymbol{\beta}$, the effects specific to country *i* denoted by α_i, indicator variables for each year represented by $Year_T$, followed by the error term ε_{it}.

Equation 3 Two-way fixed-effects model

$$y_{it} = C_{it}\gamma + \boldsymbol{X}'_{it}\boldsymbol{\beta} + \alpha_i + Year_T + \varepsilon_{it}$$

As specified in Table 3, the estimated model includes controls for potential confounders that varied over time, including the level of GDP per capita, share of population living in rural areas, and the market concentration index (Herfindahl–Hirschman). The modelled equation includes year indicator variables as controls for time trends in the dependent and policy variables.

This approach tackles various sources of bias in the identified policy impact parameter: those arising from time trends, and observable and unobservable confounders constant to each country of operation. To tackle the remaining bias arising due to the hypothetical reverse direction relationship from consumer outcomes to spectrum cost measured in per-connection terms, we rely on a two-stage, two-way fixed effects model where the spectrum cost faced by an operator (C_{it}) is modelled as a linear function of a vector of instruments $\boldsymbol{I}_{it}$, exogenous variables $\boldsymbol{X}'_{it}$, and fixed country and year effects. In the second stage equation, its fitted values $\widehat{C_{it}}$ are used as a regressor (Equation 4).

Equation 4 Instrumental variable estimator based on two-way fixed-effects model

$$y_{it} = \widehat{C_{it}}\gamma + \boldsymbol{X}'_{it}\boldsymbol{\beta} + \alpha_i + Year_T + \varepsilon_{it}$$

$$C_{it} = \boldsymbol{I}_{it}\boldsymbol{\mu} + \boldsymbol{X}'_{it}\boldsymbol{\beta} + \alpha_i + Year_T + e_{it}$$

Instrumenting spectrum cost ensures that the fitted values $\widehat{C_{it}}$ are free from influence of reverse causal relationship, thereby allowing identification of a one-directional relationship from spectrum cost to consumer outcomes. However, this identification strategy can only be valid when the instruments meet the relevant criteria, the validity of which we examine.

3. Analysis of impacts on consumer outcomes – detailed results

Two-way fixed effects model (single stage)

Estimates of the effect of spectrum cost and spectrum availability on coverage of 4G and 5G mobile networks, network speeds and latencies are shown in Table 4. These estimates were obtained using a two-way fixed effects model absorbing country and year effects, with additional controls for real GDP per capita, share of rural population and market concentration index.

We find a statistically significant negative impact of increasing spectrum cost on the deployment of 4G networks. The evaluated coefficients imply a non-linear relationship, as the estimated coefficient on the cost-to-revenue ratio squared is statistically significant. However, the shape of the estimated polynomial suggests that for higher levels of cost-to-revenue ratio, the negative effect of increasing spectrum cost slightly eases. However, this effect is small for typical values of cost-to-revenue ratio in the sample of between 3% and 12%. Evaluated at the average level of spectrum cost in our sample (spectrum cost-to-revenue ratio of about 7%), the marginal effect of increasing the spectrum cost-to-revenue ratio by 1 percentage point (pp) is a decrease in coverage of 0.44 pp.

We also estimate a positive effect of making more spectrum available. A 1% increase in spectrum assigned to an operator results in a 0.12 pp increase in 4G network coverage. Analogous results measuring the impact on coverage of 5G networks are presented for models 3 and 4. We also find a non-linear relationship between spectrum cost-to-revenue ratio and 5G coverage. The estimated effect, evaluated at a 7% cost-to-revenue ratio, suggests 0.59 pp lower coverage for a 1 pp increase in the spectrum cost-to-revenue ratio.

Analogous results measuring the impact of spectrum cost (cost-to-revenue ratio) on average network download and upload speeds are shown as models 3 and 4. The estimated non-linear relationship, evaluated at an average cost-to-revenue ratio of 7%, shows a negative impact of increasing cost-to-revenue ratio. A 1 pp increase in the cost-to-revenue ratio leads to about 0.81% lower network download speeds, and 0.68% lower upload speeds.

These results also confirm findings from other studies that increasing the amount of spectrum results in higher network speeds. [4] Our estimates show that 1% more spectrum assigned to an operator increases download speeds by 0.38% and increases upload speeds by 0.25%.

Lastly, we measure the effect of spectrum cost and availability on network latency (model 5). Network latency measures the time it takes a network to deliver a response to a request. Hence, latency measures the real-world responsiveness experienced by a user. We find that as the spectrum cost-to-revenue ratio increases, average network latency increases, resulting in a worse

[4] The impact of spectrum assignments on consumer welfare, Bahia and Castells, 2022

consumer experience. The estimated relationship is non-linear. Evaluated at a 7% cost-to-revenue ratio, we find that a 1 pp increase in spectrum cost-to-revenue ratio increases average latency by 1%. We find a significant impact of spectrum availability. A 1% increase in available spectrum results in 0.06% lower latencies.

Table 4 Impact of spectrum cost-to-revenue ratio and spectrum availability on coverage of 4G and 5G networks, download speeds and latency

Dependent variable	(1) 4G coverage	(2) 5G coverage	(3) ln(Download speed)	(4) ln(upload speed)	(5) ln(Latency)
Cost-to-revenue ratio	-0.45***	-0.61***	-0.83***	-0.70***	0.10**
	(0.03)	(0.08)	(0.08)	(0.08)	(0.05)
Cost-to-revenue ratio^2	0.07***	0.12***	0.12***	0.11***	-0.02**
	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)
ln(MHz spectrum held)	0.12***	0.16***	0.38***	0.25***	-0.06***
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Controls			Included		
Absorbed fixed effects			Year and country		
Observations	5,648	1,519	6,085	6,085	6,085
R-squared	0.71	0.79	0.85	0.76	0.84

Note: Standard errors in parentheses. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

Additional results (not presented) show that clustering standard errors at an operator level generally does not affect the statistical significance of results outlined above to alter the conclusions. When deciding on the clustering level of standard errors at the country level, we considered the process in which the spectrum cost and spectrum available to operators are determined.

The spectrum cost faced by operators is generally determined at the country level and primarily driven by the approach taken by the regulator. This is supported by a large degree of correlation in spectrum cost (per unit of revenue or per connection) among operators in the same country. Similarly, the total amount of spectrum available to operators is also determined by the national regulator's decision to open it to assignment. Hence, treatment in the form of policy choice on spectrum cost and spectrum availability is assigned at the country level, with some additional variation stemming from individual operator-driven choices on how much spectrum to acquire and at what price, based on specific strategies. In cases where assignment to treatment is clustered at a certain level, in this case at the country level, it is recommended to align the standard error clustering level to the assignment of treatment.[5]

In the following tables, we examine the impact of spectrum cost defined using an alternative metric: amortised cost of all active licences per connection ($2023 PPP/total mobile connections).

Table 5 shows the estimated impact on coverage of 4G and 5G networks, network speeds and latency. We estimate a non-linear relationship with spectrum cost. Evaluated at close to the average cost per connection ($2023 PPP/mobile connection), we find that a doubling of spectrum cost lowers 4G coverage by 5.1 pp. We find the same magnitude of the effect on 5G network coverage. We also find that a doubling of spectrum cost per connection results in 6.2% lower download speeds when evaluating the marginal effect at the average spectrum cost of about $3 PPP/connection. Doubling of available spectrum increases download speeds by 39%, and upload speeds by 26%. This is similar to the magnitude estimated in previous studies.[6] [7] Similar to the cost-to-revenue cost metric, we find mixed significance of the relationship with latencies.

Table 5 Impact of spectrum cost per connection and spectrum availability on coverage of 4G and 5G networks

Dependent variable	**(6)** **4G coverage**	**(7)** **5G coverage**	**(8)** **ln(Download speed)**	**(9)** **ln(Upload speed)**	**(10)** **ln(Latency)**
ln(Cost per connection)	-0.03***	-0.03***	-0.04***	-0.04***	0.004
	(0.00)	(0.01)	(0.01)	(0.01)	(0.005)
ln(Cost per connection)^2	-0.01***	-0.01***	-0.01***	-0.01***	0.003***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.001)
ln(MHz)	0.13***	0.16***	0.39***	0.26***	-0.063***
	(0.00)	(0.01)	(0.01)	(0.01)	(0.008)
Controls			Included		
Absorbed fixed effects			Year and country		
Observations	6,146	1,633	6,630	6,627	6,630
R-squared	0.71	0.89	0.85	0.83	0.83

[5] When Should You Adjust Standard Errors for Clustering? Abadie, Athey, Imbens & Wooldridge, 2023
[6] The impact of spectrum assignment policies on consumer welfare, Bahia & Castells, 2022
[7] The Impact of Spectrum Set-Asides on Private and Public Mobile Networks, GSMA Intelligence, 2024

Note: Standard errors in parentheses. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

Instrumental variable estimates

Next, we present the key results based on instrumental variable estimators, aiming to address the remaining sources of endogeneity between spectrum cost and consumer outcomes. Given the need to instrument the cost metrics, we rely on linear models and do not include the additional polynomial terms for the cost of spectrum.

IV estimates based on the cost per connection metric are presented in Tables 6 to 8. Estimated impact coefficients generally conform to earlier single-stage results, but the magnitude of the estimated negative effect of spectrum cost is higher.

For example, for the impact on 4G network coverage, the IV estimator yields the average effect at 35 pp lower 4G network coverage for the doubling of spectrum cost per connection. This is in contrast to the lower marginal effect based on single-stage estimation, at 5.4 pp lower 4G coverage for the doubling of spectrum cost per connection.

We propose a few potential sources of a difference between the single-stage estimator and the IV estimator. Firstly, it is possible that the single-stage estimate is affected by a negative bias stemming from omitted variables. As discussed earlier, the value of spectrum can be lower where demand for mobile services is not expected to grow as much as elsewhere. This will simultaneously determine lower spectrum cost per connection, but also lower quality of service due to limited demand and commercial viability. This effect takes the opposite direction to the expected relationship between spectrum cost and consumer outcomes, cancelling some of the observed impact in single-stage estimates.

Secondly, the parameter identified by the IV estimator is different due to use of instrumental variable. In the context of potential non-linear and heterogeneous impacts, the IV estimate can identify the local average treatment effect on a specific sub-group of population for which the instrument was an influential factor contributing to the cost of spectrum. We discuss this in more detail in the section that follows.

The effect on 5G network coverage is more similar to the estimate based on a single-stage equation (12.6 pp against 5.4 pp lower coverage in response to the doubling of spectrum cost per connection). As we rely on the same set of instruments to obtain fitted values of spectrum cost per connection, the first-stage results are similar to the model estimating 4G network coverage. However, the strength of instruments diminishes due to a much lower sample size.

Table 6 Impact of spectrum cost per connection and spectrum availability on network coverage: instrumental variable estimates

Second stage	**(11) Second-stage**	**(12) Second-stage**
Dependent variable	**4G network coverage**	**5G network coverage**

	ln(Cost per connection)	-0.346***	-0.126**
		(0.124)	(0.058)
	ln(MHz)	0.242***	0.204***
		(0.047)	(0.019)
	Controls	Included	
	Absorbed fixed effects	Year and country	
	Observations	2,457	979
	R-squared	0.745	0.500
First stage	**Dependent variable**	**(11) First stage ln(Cost per connection)**	**(12) First stage ln(Cost per connection)**
	Short-term debt	-0.046***	-0.009
		(0.010)	(0.016)
	Govt. primary balance	-1.548**	-1.074
		(0.640)	(0.983)
	Share of auctions	0.517***	0.030
		(0.099)	(0.154)
	Regional cost-to-revenue ratio	-0.112	6.783
		(0.141)	(4.350)
	Share of binding reserve prices	1.101***	0.644***
		(0.135)	(0.238)
	Controls	Included	
	Absorbed fixed effects	Year and country	
	Observations	2,456	976
	R-squared	0.672	0.747

Note: Standard errors in parentheses. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

The IV estimate based on the cost per connection yields a point estimate of 24% lower network download speeds for the doubling of spectrum cost, and 9.4% lower upload speeds, though the statistical significance of the latter is below the 5% threshold (p=8%). The estimated impact of spectrum amount is also similar to that from earlier equations.

Table 7 Impact of spectrum cost per connection and spectrum availability on download and upload speeds: instrumental variable estimates

Second stage	**Dependent variable**	**(13) Second-stage Average network download speed**	**(14) Second-stage Average network upload speed**
	ln(Cost per connection)	-0.237***	-0.094*

		(0.063)	(0.055)
	ln(MHz)	0.366***	0.255***
		(0.035)	(0.031)
	Controls	Included	
	Absorbed fixed effects	Year and country	
	Observations	2,499	2,499
	R-squared	0.830	0.731
First stage		**(13)**	**(14)**
		First stage	**First stage**
	Dependent variable	**ln(Cost per connection)**	**ln(Cost per connection)**
	Short-term debt	-0.035***	-0.035***
		(0.010)	(0.010)
	Govt. primary balance	-1.498**	-1.498**
		(0.645)	(0.645)
	Share of auctions	0.367***	0.367***
		(0.098)	(0.098)
	Regional cost-to-revenue ratio	-0.113	-0.113
		(0.143)	(0.143)
	Share of binding reserve prices	1.230***	1.230***
		(0.141)	(0.141)
	Controls	Included	
	Absorbed fixed effects	Year and country	
	Observations	2,499	2,499
	R-squared	0.669	0.669

Note: Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

Impact on latencies (Table 8) is estimated at 8% lower latency for doubling of spectrum cost, which takes an unexpected direction. Similarly, an increasing amount of spectrum is estimated to be associated with higher latencies. These results do not conform to the results of no statistically significant impact obtained using single stage models. This could be influenced by an oversimplification of the model – due to the presence of a non-linear relationship, for example.

Table 8 Impact of spectrum cost per connection and spectrum availability on average network latency: instrumental variable estimates

		(15)
Second stage		**Second stage**
	Dependent variable	**ln(Average all-network latency)**

ln(Cost per connection)	-0.083***
	(0.031)
ln(MHz)	0.039**
	(0.017)
Controls	Included
Absorbed fixed effects	Year and country
Observations	2,499
R-squared	0.877

First stage		**(15)** **First stage**
	Dependent variable	ln(Cost per connection)
	Short term debt	-0.035***
		(0.010)
	Govt. primary balance	-1.498**
		(0.645)
	Share of auctions	0.367***
		(0.098)
	Regional cost-to-revenue ratio	-0.113
		(0.143)
	Share of binding reserve prices	1.230***
		(0.141)
	Controls	Included
	Absorbed fixed effects	Year and country
	Observations	2,499
	R-squared	0.669

Note: Probability values in parentheses. Probability values calculated using robust standard errors. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

Table 9 presents the weak identification test results, showing joint significance of the instruments in all estimated IV equations with the exception of the 5G coverage equation, likely due to a lower sample size.

Table 9 Weak identification test – IV estimates relying on spectrum cost per connection measure

	(11) **4G coverage**	**(12)** **5G coverage**	**(13)** **Download speed**	**(14)** **Upload speed**	**(15)** **Latency**
F statistic (joint significance of instruments)	25.08	2.19	23.32	23.32	23.32

Critical value for 10% max. rel. IV bias	10.83	10.83	10.83	10.83	10.83
Sample size	2457	979	2499	2499	2499

Source: GSMA Intelligence

Discussion of the results

We emphasise the results based on the cost-to-revenue ratio, as this metric of spectrum cost can be superior in eliminating the influence of endogenous relationships that could affect models relying on the cost-per-connection metric.

For the estimates based on cost per connection, we do not choose the preferred estimate between single-stage and two-stage IV estimates. Rather, we treat the two-stage IV estimates based on the cost per connection metric as robustness checks for two reasons.

First, we find limited support for hypothetical sources of endogeneity that could not be addressed by a two-way fixed-effects estimator. As discussed earlier, we do not see a clear argument for a potential source of endogeneity between spectrum cost and consumer impacts due to a potential reverse causal relationship from consumer impacts to spectrum cost. Some remaining confounding can potentially arise due to simultaneity – for example, operators who persistently underestimated the quality of service demanded by consumers or were inefficient at operating the network could fail to realise the planned revenues, leading to an elevated spectrum cost-to-revenue ratio. However, it is unlikely that this would have been a persistent pattern across operators in multiple countries and across time. We therefore deem this to be an unlikely cause of an endogenous relationship. Therefore, the only remaining sources of endogeneity that are of concern are limited to the spectrum cost-per-connection metric, given that spectrum cost per connection can be driven by market factors that also drive consumer outcomes.

Second, instrumental variable estimates can be affected by heterogeneity in treatment effects, for example, if the relationship between spectrum cost and consumer outcomes is not linear. In such cases, instrumental variable estimation will identify specific local average treatment effect (LATE), which – depending on the selected instrumental variable(s) – can be identified at different levels and for different subgroups of population.[8] Using a hypothetical example, reserve prices may be an influential factor that can typically elevate the spectrum cost per connection in the range of $3–4, while governments seeking additional revenue to cover the cost of maturing short-term debt can take the total cost of spectrum to even higher levels, at $5–8. Depending on a specific case, the cost of spectrum may be influenced by a different exogenous instrument or a combination of instruments. In addition, operators in countries where the instrumental variable is a driving factor behind spectrum cost may be a specific subgroup of the overall population of operators. Hence, the estimated effect of a higher cost of spectrum will be based on the treatment effect on the specific group affected by the instrumental variable, which may respond differently to the cost of spectrum compared to the entire population average. For example, countries which set high

[8] Identification and Estimation of Local Average Treatment Effects, Imbens and Angrist, 1994

reserve prices to acquire additional revenue from the sale of spectrum could also be relying on other ways to raise revenues from the sector – for example, through sector specific taxes.

Hence, the estimate of the average treatment effect (ATE) from a single-stage estimator and the LATE identified using instrumental variables may not be directly comparable. Rather, we remain satisfied that the overall direction of impact and its estimated statistical significance remain aligned across estimators.

Given the potential heterogeneity and sensitivity of the estimated LATE to the choice of instrumental variable(s), we do not conduct a likelihood ratio test comparing the single-stage estimate impact coefficient to the coefficient obtained from the instrumental variable estimate. Similarly, we do not rely on the test for overidentifying restrictions, as different instruments identifying different LATE could lead to rejection of joint exogeneity of the instruments.[9]

[9] A cautionary note on tests of overidentifying restrictions, Parente and Santos Silva, 2012

4. Analysis of determinants of spectrum prices

The determinants of spectrum prices have been evaluated using hedonic analysis of licence-level data. Hedonic analysis decomposes the value of individual spectrum licences via regression analysis. The licence price adjusted for the cost of capital using WACC (dependent variable) is modelled as a linear function of various licence characteristics, such as its duration (in years), bandwidth (in MHz) and similar. The adjustment for the cost of capital is based on the same WACC estimates and formulae as outlined in Chapter 1 in the context of spectrum price benchmarking analysis.

Regression analysis estimates coefficients that can be interpreted as measures of the average effect of a unit change of each factor on the price of a licence. Table 10 presents the estimated coefficients for the basic covariates of spectrum prices. Given the functional form of the estimated equation, the coefficients measure the relationship as an elasticity – that is, the percentage change in final price of assignment in response to 100% increase in the explanatory variable.

Table 10 Hedonic regression of the determinants of spectrum prices: basic determinants of spectrum prices

Dependent variable:	**ln(Final assignment price, adjusted for cost of capital)**
Bandwidth in MHz (ln)	0.887***
	(0.00)
Duration in years (ln)	0.874***
	(0.00)
Population (ln)	1.207***
	(0.00)
Average revenue per connection (ln)	0.300***
	(0.00)
Intercept	-3.58***
	(0.00)
Other control variables	Included for frequency band and assignment type
Eliminated fixed effects	None
Number of observations	1,329

Note: Probability values in parentheses. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

Table 11 presents the estimated coefficients for assignment types. Given the functional form, the exponents of the estimated coefficients measure the relative price of assignment in relation to auctions. For example, the exponent of the coefficient on administrative assignment is 0.867, which means that, on average, the administrative assignment was priced at 86.7% of the price of a similar assignment that relied on auction.

Table 11 Hedonic regression of the determinants of spectrum prices: assignment type analysis

Dependent variable:	**Ln (Final assignment price, adjusted for cost of capital)**
Assignment type (reference type: Auction):	
Administrative assignment	-0.142*
	(0.53)
Renewal	-0.242*
	(0.21)
Intercept	-2.727***
	(0.00)
Other control variables	Included for frequency band, bandwidth (MHz), duration, GDP per capita, population, average revenue per connection
Eliminated fixed effects	Year and country effects
Number of observations	1,319

Note: Probability values in parentheses. Asterisks attached to coefficients indicate probability levels: *** p<.01, ** p<.05, * p<.1.

Source: GSMA Intelligence

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