Spectrum Licence Duration and Capital Investment

An empirical assessment

Prepared for

Ofcom

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1. INTRODUCTION AND EXECUTIVE SUMMARY

1. The Communication Act of 2003 establishes OFCOM principal duty as the promotion of the interests of citizens and consumers in communications markets ("where appropriate by promoting competition")[1] and specifies a list of things that "OFCOM are required to secure in the carrying out of their functions", with the first item being "the optimal use for wireless telegraphy of the electro-magnetic spectrum".[2] The Act also states that in performing its duties OFCOM must take into account, among other things, "the desirability of encouraging investment and innovation in relevant markets".[3]

2. These goals can be roughly translated in economics terms as stating that OFCOM's spectrum licensing policies should aim to maximize consumer welfare, taking into account both *static* and *dynamic* efficiency.

3. Static efficiency calls for spectrum rights to be given to those firms who are best placed to use them to provide high-quality services at low cost, while ensuring that there are enough firms with sufficient spectrum holdings to compete effectively and thus keep prices low for consumers.[4]

4. Dynamic efficiency further requires that current and prospective spectrum rights holders have the appropriate incentives to invest in the quality of network infrastructure and technologies, so that they will in fact be able to provide good service at low cost and thus make optimal use of the spectrum.

5. In principle, it is possible that the two objectives of static and dynamic efficiency may push in opposite directions. For example, OFCOM has recently investigated the possibility that investment incentives, and thus ultimately service quality, may be harmed by policies that limit industry concentration.[5]

6. This report considers another potential policy variable that may have opposing effects on static and dynamic efficiency, namely the duration of spectrum licenses. On the one hand,

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1 *Communications Act 2003*, section 3, paragraph 1.

2 *Communications Act 2003*, section 3, paragraph 2. The *Wireless Telegraphy Act 2006*, part 6, paragraph 116 defines wireless telegraphy as including the conveyance of any "messages, sound or visual images" over the electromagnetic spectrum.

3 *Communications Act 2003*, section 3, paragraph 4.

4 The use of spectrum auctions and caps on spectrum holdings is typically justified by considerations of static efficiency. The firms who are best placed to provide good service at low cost are typically those who can make most money from the use of the spectrum and thus who can bid more – and be more likely to win – in an auction. Spectrum caps, or equivalent restrictions, are used to prevent the most efficient firms (or any other firms) from winning so much spectrum that their rivals would be unable to compete effectively in downstream markets, leading to worse deals for consumers.

5 See OFCOM's study on "Market structure, investment and quality in the mobile industry", Economics Discussion Paper Series, Issue Number 1, December 2020, available at https://www.ofcom.org.uk/research-and-data/economics-discussion-papers/mobile-market-consolidation. The study found no evidence that countries with more concentrated markets have higher investments or higher service quality.

as market conditions and technologies change, the set of most efficient spectrum holders is likely to change and secondary spectrum markets in long-duration spectrum licenses may be less efficient in reallocating spectrum than periodic re-auctioning of licenses with shorter durations. On the other hand, shorter license durations increase firms' uncertainty about the future availability of spectrum (to themselves and to competitors) and this can lead to lower investments in network infrastructure, as the expected horizon over which firms can expect to recoup these investments is shortened.

7. So, is there a trade-off between allocative efficiency (shorter licenses re-allocating spectrum to the highest-value users more often) and dynamic efficiency (longer licenses inducing higher investment levels)? The theoretical arguments are actually not clear-cut. First, higher investments are not a synonym of dynamic efficiency – after all, the optimal level of investments must be finite and further increases beyond that point would, by definition, be inefficient. Furthermore, if it is likely that some new, highly efficient operator is going to appear soon and replace the incumbent operators, it may be inefficient for the latter to invest much in assets that could not be transferred to the former – and a sequence of auctions for short-term licences could provide just the right level of investment incentives.[6] Second, if secondary spectrum market worked well, then the duration of licenses would be largely irrelevant as firms would voluntary sell spectrum rights to more efficient rivals when they appear – and anticipate this possibility of remaining without that spectrum in their investment plans, thus also reducing the expected time horizon over which investment costs have to be recouped.[7] Third, shorter planning horizons do not necessarily imply lower investments, e.g., if the level of investments required to make use of the spectrum is relatively fixed and such that it remains profitable even with a shorter planning horizon. License with shorter durations may also lead to higher investments, at least in the short term because they are more likely to be won by firms who plan to put them to use right away rather than hoarding the spectrum (without investing in complementary assets) for potential future uses.[8] Finally, shorter license need imply shorter planning horizons because spectrum holders may be reasonably convinced that they will be able to win the licence again at renewal time.

8. This report thus seeks to empirically investigate the relationship between mobile spectrum license duration and capital investment.

9. We use spectrum auction data for different mobile licenses across EU and non-EU OECD countries which also include data on license duration. We combine this data with operator-specific data on CAPEX per capita over a 10-year period (2011Q1-2021Q2), and with further country- and operator-specific variables.

10. There are several factors that complicate an analysis of the relationship between spectrum license duration and capital investment. First, firms typically have more than one spectrum license, each awarded at different times and with different durations. For example, a firm may spend on maintaining their 3G infrastructure, whose license may be expiring soon, while they build up their 4G infrastructure, which relies on a newly acquired license.

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6 See section 2 for further discussion.

7 We understand that OFCOM has serious concerns about the well-functioning of spectrum secondary markets.

8 This hoarding behaviour is not necessarily inefficient, as the option value of maintaining flexibility over the use of the spectrum for spectrum holders may be significant, much as the flexibility afforded by short license durations is significant for the regulator's objectives.

However, the available capital expenditure data does not differentiate between investments related to the use of the spectrum corresponding to different licenses, hence it is not possible to directly identify the effects of individual license durations on operators' investment choices.

11. Second, the effects of license durations may be different at different points in the investment cycle of any given generation of mobile networks. For example, whether the license lasts for 20 or 15 years may not matter much for early investment, as the initial infrastructure is required for both. However, the investment incentives firms face in the 15th year of the license may differ significantly, as that would be the last year for which spectrum availability is guaranteed under the 15-year license while five more years would be guaranteed under the 20-year license, at least if significant capital investment in the network is still needed at that time. The fact that we only have aggregate (firm-level) data on capital investments for about ten years severely limits the analysis of these long-term effects.

12. Third, the effective duration of licenses is sometimes unclear. In some cases, licenses have been issued for a given fixed duration and have then been extended or renewed without undergoing a new selection process – and without the conditions for these extensions being clearly specified (or even mentioned) in the original tender documents. It is then difficult to establish when the license holders became convinced that they would be able to keep their licenses beyond the original term and adjusted their investment plans accordingly. Even when the possibility of automatic renewal of the licenses was in the cards from the start, a judgement call has to be made to decide whether there was sufficient certainty on this point to consider these licenses as having a *de facto* indefinite duration.[9]

13. Because of these complications, it is not possible to develop a single comprehensive model of the relations between license durations and investment level. Instead, we adopt several approaches that allow to test different hypotheses based on different cuts of the data.

14. We start by revisiting (in section 4.1 of this report) what is, to the best of our knowledge, the only previous work in the economic literature exploring the empirical relationship between investment and spectrum license duration, namely the 2019 paper by Jeanjean, Lebourges and Liang, henceforth referred to as JLL.[10] JLL focus on the correlation between operators' quarterly capital expenditure "per capita"[11] and two measures of license duration (average initial duration across all the operator's licenses and the initial duration of the last license to be acquired) in a cross-country panel analysis of 14 European countries and claim to find a large and statistically significantly positive effect of license duration on investment levels. However, we find that this effect is much smaller and often statistically insignificant when we apply JLL's model to our data, even when restricted to the same 14 countries considered by JLL. Moreover, we highlight several methodological concerns with JLL's analysis which, once addressed to the extent possible while keeping the structure of the model, further reduce the size and significance of the claimed effects. In sum, we

9 The decisions on this point have been made in agreement with OFCOM's team. The presence of license with indefinite duration also creates some technical problems in that duration can no longer be considered a continuous variable. We discuss this issue in more detail in section4.

10 Jeanjean, Francois, Marc Lebourges, and Julienne Liang. "The impact of license duration on tangible investments of mobile operators." *Telecommunications Policy* 43.9 (2019): 101835.

11 The definition of "per capita" in JLL (and in some of the analyses in this report) is not standard; see section 4 for the details.

conclude that, on the basis of the data available to us, JLL's model does not provide evidence of a robust relationship between investments and license durations.

15. We then consider (in section 0) whether a relationship between investments and license durations can be established at the country level, rather than at the operator level. More specifically, for each country in our dataset we take the quarters when a spectrum auction occurred and compare the average operators' investments in the next 1 to 5 years for different values of the average duration of the licenses awarded in that quarter. Even after controlling for GDP per capita and population density, we do not find any evidence of a positive relation between license duration and investment; if anything, we find that longer-term licenses (and indefinite-term licenses) are associated with lower investment levels, though the estimated relationship is neither monotonic, nor statistically robust.

16. Our next analysis returns to focusing on operator-level CAPEX investments. In section 4.3 we investigate the change in operators' investments in the two years following the award of a spectrum license compared to their level one year before the award. As expected, we find that investment levels increase after obtaining a license. However, once again, we find no evidence that longer-term and indefinite term licenses are associated with higher investment levels, with the results pointing tentatively (and non-robustly) in the opposite direction.

17. As noted above, it is possible that the effects of license duration on investments are felt mainly in the later parts of a license life. Perhaps the winners of a spectrum auction would invest in the more profitable areas of their country right away regardless of the duration of the license – after all, if they bid for some spectrum rights they should have planned to use them somewhere – but expansion of their networks in less profitable areas may be postponed (e.g., for lack of financing or managerial resources) and possibly abandoned if the remaining time on the license is too short. Since we do not have investment data disaggregated between, say, more profitable urban areas and less profitable rural areas, we cannot test this specific theory directly. However, we can investigate whether operators' investments are indeed lower when closer to the expiration of the licence. We do so in section 4.4 by computing operators' overall level of investments between the 11th and the 15th year of their 3G licenses and observing how this level differs between cases where the 3G license had a 15-year duration (hence these were the last five years of the license) and cases where it had a 20-year or indefinite duration (hence there were still another five or more years on the license to recoup the cost of these investments). The results, also after controlling for other determinants of investment (GDP per capita, population density, whether the operator had also acquired a 4G or 5G license), point once again to a negative, albeit often statistically insignificant, relation between license duration and investments.

18. Finally, while investments are desirable, they are not an end goal in themselves. They mainly contribute to consumer welfare by allowing operators to offer higher quality service, namely broader coverage, higher transmission speed, lower latency, etc. In section 4.5 we investigate whether our data show a positive effect of investment on one specific measure of service quality (increases in average download speed in the transition from 3G to 4G) and whether, regardless of investment levels, this measure is correlated directly with license duration. We find that higher investments are in fact associated with faster increases in download speed, but (unsurprisingly, given the results of the previous analyses) no clear relation between license duration and download speeds. In both regards, sample sizes are too small to find any statistically significant results.

19. We have already mentioned the intrinsic limitations of the available data: operator level capex data are both noisy and overly aggregated, license durations are not always well-

defined, and the time period for which the data are available barely covers one investment cycle, stretching from the end of the 3G cycle to the beginning of the 5G one. Therefore, we cannot exclude that the results of the analyses in this report may be merely due to such limitations, nor avoid the customary "more research is needed". But that additional research is bound to require more time, and more investment cycles, to pass before adequate data are available. Meanwhile, policy decisions have to be made on the basis of the currently available evidence. And, in sum, we found no evidence that longer (or indefinite) license durations are associated with higher investment levels or better outcomes for consumers.

20. The remainder of the report is organized as follows. Section 2 provides a brief review of the literature. Section 3 describes the data used for the analyses in the report. Section 4 is the core of the report and discusses the methods and results of the analyses. Section 5 summarizes our conclusions and outlines some potential avenues for further research.

2. RELATED LITERATURE

21. There are several strands of the economics literature that are tangentially related to the problem investigated in this report, though to the best of our knowledge none addresses it directly.

22. In order to provide a reference point to assess the relevance of the literature, we can consider as a benchmark the case in which the relevant markets – and in the particular the secondary spectrum markets – mirrored the ideal standard of perfectly competitive, frictionless markets (or those of fully efficient bargaining). In this case, there would be no trade-off between static and dynamic efficiency and investment incentives would be the same regardless of licence duration. Even if the licence duration was very long (or infinite), licence holders would still have an incentive to sell their licences to a firm that could extract more value from them. The probability that such a firm appears depends itself on the license holder's investments in network infrastructure, e.g., if the investments are complementary to spectrum holdings, then they would increase the value of holding on to the license and push forward into the future the moment in which a yet more efficient user of the spectrum arrives in the market.[12] Then either this effect is so strong that this arrival does not occur before the expiration of the license and we have no trade-off with static efficiency (because the current license holders is always the most statically efficient one), or the license holder must plan its investments so that their cost can be recouped before this arrival. But that is the same planning horizon that current license holders would use even if the license duration was shorter since they would expect to win the next spectrum auctions precisely because it occurs before a more efficient firm is expected to arrive in the market. Hence, in this idealized world, licence duration has no effect on investments, which are set at the efficient level in any case.

23. The literature on investment incentives in more standard auction settings shows that the logic of this efficiency result may continue to hold, but only under some conditions – and does not address the issue of optimal license duration. This literature considers a license holders' incentives to invest in raising their own valuation of the licence before the license

12 We are assuming here that the investments are "private" (i.e., they do not affect the value of the spectrum to firms other than the license holder) and non-transferable (i.e., not embodied in goods that could be sold together with the spectrum rights without loss of value), which seems reasonable in the context of network investments. In the present context of a hypothetical perfect competition world, these assumptions simplify our discussion, but they are not actually necessary, as investment would be efficient anyway.

expires and it is once again put up for auction. For some types of auction formats (including second-price auctions and the more general Vickrey-Clark-Groves mechanisms), there are equilibria in which the license holder chooses the efficient level of investments, though other, inefficient equilibria may also be present unless further conditions are imposed – and only inefficient equilibria may occur with other auction formats.[13] However, we have not find any paper in this literature that addresses the issue of what the licence duration should be in cases where inefficient equilibria cannot be avoided.

24. A partial exception is the paper by Weyl and Zhang (2022) who consider a novel auction mechanism in which license holders have some degree of partial ownership in the spectrum and this degree can be interpreted as roughly equivalent to (the inverse of) license duration.[14] However the correspondence is not exact and, in any case, the paper addresses the case in which the investment in question has a public good nature (i.e., it benefits also future spectrum holders other than the one making the investment) and thus seems inapplicable to the case of investments in network infrastructure.

25. The paper by Saha *et al.* (2021) is in a sense a polar opposite of this literature in that it does focus on the optimal duration of spectrum license, but does not really consider investment incentives.[15] In their model, investment considerations are only mentioned as an out-of-model justification for the *assumption* that fewer firms may decide to bid for spectrum rights if the licence duration is too short, while excessively short durations also reduce the number of firms because of assumed financial constrains make the prices of licenses unaffordable. The paper also adopts several other non-standard modelling assumptions that, in our view, make it unsuitable for the purpose of informing policy decisions.

26. In terms of empirical research, the literature on the determinants of mobile network investments has mostly focused on the relation between market concentration and investment incentives and we refer to OFCOM's discussion paper cited above for further references. We are aware of only one paper that addresses our main question of interest directly, namely the JLL paper cited above; we discuss this extensively in section 4.1.

27. The problem of choosing optimal license durations is superficially similar to the one of choosing optimal patent lengths. In both cases, there is a potential trade-off between static and dynamic efficiency, but the issues are quite different. In the patent context, the object to be allocated is non-rival (i.e., in principle, everyone could use a patented technology at the same time), so longer patent lengths reduce static efficiency by preventing such use, as wells as by extending the period in which the patent holder can exercise (distortionary) monopoly power in downstream markets. The focus on promoting innovation rather than generic investment also affects the kind of dynamic efficiency issues at stake, e.g., patents

13 For more details and further pointers to the literatures see for example: Tomoeda, Kentaro (2019), "Efficient investments in the implementation problem", *Journal of Economic Theory*, vol. 182, pp. 247-278; Dirk Bergemann and Juuso Valimaki (2019), "Dynamic Mechanism Design: An Introduction", *Journal of Economic Literature*, vol. 57, pp. 235-274;. Mohammad Akbarpour, Scott Duke Kominers, Kevin Michael Li, Shengwu Li, and Paul Milgrom (2022), "Investment Incentives in Truthful Approximation Mechanisms", working paper, available at http://web.stanford.edu/~mohamwad/InvestmentIncentives.pdf,

14 E. Glen Weyl and Anthony Lee Zhang (2022), "Depreciating Licenses", *American Economic Journal: Economic Poilicy*, vol. 14, no. 3, pp. 422-448.

15 Gourav Saha, Alhussein A. Abouzeid, Zaheer Khan, and Marja Matinmikko-Blue (2021), "On the Optimal Duration of Spectrum Leases in Exclusive License Markets with Stochastic Demand", arXiv:2102.09153v1.

with longer duration (and/or broader scope) may reduce other firms' incentives to invest in follow-up or complementary innovation. In any case, the patents literature is still hotly contested, with some economists even arguing for the complete abolition of patents.[16]

28. The literature on contract theory and transaction cost economics also addresses a similar problem, namely the choice between short-term and long-term contracts in supply relationships. In fact, an important motivation of this literature is to explain why firms sometimes choose long(er)-term contracts or vertical integration (or some hybrid organisational form) instead of relying on short-term or spot deals. Once again, however, the issues involved are somewhat different from those involved in the choice of spectrum license durations, e.g., the possibility of hold-up (i.e., the ex-post appropriation of the value of relation-specific investments), risk sharing and consumption smoothing in repeated principal-agent problems, or the reduction of other transaction costs.[17] A review of the empirical strand of this literature is beyond the scope of this report, though we understand that it tends to support the notion that longer term contracts are indeed associated with higher level of investments in long-lived, relation-specific assets. These results are, however, quite industry-specific (e.g., in the type of assets involved and in what duration can be considered), and it is not clear that they would be applicable to the issue addressed in this report.

3. DATA SOURCES

29. In this section, we describe the different datasets used for our analysis.

Analysys Mason Spectrum Auction Data

30. This dataset provides information on past (combinatorial and non-combinatorial) spectrum auctions for a period between 1994Q1 and 2021Q2. The dataset includes information on winning operator, auction price, reserve price, license duration, and estimated population covered by the spectrum licenses in the auction. While some countries only grant national spectrum licenses, others also grant licenses (and run spectrum auctions) for different regions.

16 For more details and further pointers to this literature see for example: Suzanne Scotchmer, *Innovation and Incentives*, The MIT Press, 2004; Michele Boldrin and David K. Levine, *Against Intellectual Monopoly,* Cambridge University Press, 2010; James Bergin (2018), "Patent Policy, investment and social welfare", *International Journal of Industrial Organization*, vol. 61, pp. 439-458.

17 The contract theory and transaction costs literatures are exceedingly vast. Some of the more relevant papers for the purpose of this report are cited in the introduction of the following paper: Pierre Dubois and Tomislav Vukina (2016), "Incentives to Invest in Short-Term vs Long-Term Contracts: Theory and Evidence", *The B.E. Journal of Economic Analysis & Policy*, vol. 16, no. 3, pp. 1239-1272.

- We consider only mobile spectrum licenses that have been awarded in a spectrum auction. Other spectrum rights that have been allocated via "beauty contests" or other administrative procedures have been excluded from the analysis since they may have different implications for investment incentives (e.g., the regulatory authorities may have used the firms' investment plans as one of the criteria for the allocation, either implicitly or explicitly). Similarly, we exclude licences acquired in secondary spectrum markets, as the acquisitions may came at different points of the investment cycle and/or being merely incremental with little impact on investments.
- We assume the starting date of the license to be the same as the bid date for the spectrum. We understand that licenses can officially start up to 6 months after the bid data;[18] however, the starting date of licenses is missing in many cases, so we use the always available bid date for consistency. Accordingly, we calculate the license's end date as the bid date plus the duration of the license.
- As agreed with OFCOM, we categorise the UK, the US, the Czech Republic, Spain, Estonia and Latvia as having licenses with indefinite duration for the purposes of our own analyses in sections 0-4.5. However, when applying JLL's model to our data in section 4.1 we maintain what we believe to be their assumption that the duration of the licences in these countries was the (possibly just nominal) one originally mentioned in the licence award, as provided in the database.
- We manually identify countries that have renewal policies.[19] For these countries, we assume that they are allowed to renew once, as opposed to consecutively which would make licenses equivalent to indefinite licenses. We assume that a renewed license has the same duration as an original one, except for Canada and Hungary, where the data explicitly states the renewal to be for a duration of 10 years and 5 years, respectively. Again, we do not factor this in when applying the data available to us to the empirical model of JLL.
- We homogenise names across time in the auction dataset and across datasets. Often these are obvious, e.g., "ORANGE" in Slovenia is the same as "Orange Slovenia" in a different dataset. Moreover, many operators change names over time, and we have tried to capture the identity of operators over time.

OMDIA WCIS, Spectrum Holdings, and Interconnect Benchmark Data

31. The OMDIA WCIS database provides quarterly country-operator level information between 2011Q1 and 2021Q3 on capital expenditures (CAPEX), average revenue per user ("ARPU"), and operator subscriptions.

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18 For the application of the JLL model, this inaccuracy only affects the calculation of when licenses expire. It's unclear how JLL deal with this problem, given that they are using the same dataset with the same limitations. For the remaining analyses, it is not clear there are any effects. This is because most of the uncertainty around spectrum availability is resolved with the auction, regardless of the starting date of the license. A concerning possibility is if the delay between auction and license start is correlated with the duration of the license itself, although there is no obvious reason that would be the case.

19 We identify the following countries as having renewal policies: Australia, Canada, Hungary, Italy, Japan, Korea, Mexico, Poland, Portugal, Slovakia, Spain, New Zealand. Source: https://www.oecd-ilibrary.org/sites/1343f784-en/index.html?itemId=/content/component/1343f784-en#annex-d1e20924.

32. This dataset is further accompanied by OMDIA Spectrum Holdings Data that provides information on operators' spectrum holdings and frequencies. We further use OMDIA Interconnect Benchmark data that provides country and country-operator specific information on Mobile Termination Rates (MTR) and on origination charges.

Analysys Mason Telecom Matrix Data

33. For all European countries we use additional quarterly data from the Analysys Mason Telecom Matrix, which gives additional information on a country and country-operator level on ARPU, average spend per user (ASPU), the number of connections, market penetration, retail and service revenues, and overall traffic. Additionally, it has data on when operators entered the market (e.g., "first entrant"). Moreover, these data also give information on market shares of different operators, including MVNOs.[20]

Ookla Download Speed Data

34. The database provided by Ookla gives quarterly information on average download speeds, our measure of network quality, on a country-operator-quarterly level.[21] We see some instances where there are duplicate entries, i.e., there are two speeds reported for the same operator country and quarter. For these, we set the download speed to the average of the duplicates.

OECD/EUROSTAT Economic Indicator Data

35. Finally, we augment the above data with country-specific quarterly and annual economic indicators such as GDP, GDP per capita, interest rates, population size, and population density in terms of population per square kilometre.[22]

4. EMPIRICAL MODELS OF THE IMPACT OF LICENCE DURATION ON INVESTMENT AND NETWORK QUALITY

36. We have noted in section 2 that we cannot establish a relation between license duration and investments on a purely theoretical basis. Its existence, as well as its magnitude and direction, are an empirical matter – and the focus of this section.

37. In order to better understand the nature of the challenges in developing this empirical analysis, it is useful to begin by considering how one would ideally assess the relationship between spectrum license duration and capital investment. In principle, we would like to compare the investment of a MNO in the "factual" scenario (i.e. for a given number of licenses with associated spectrum durations) with what the same MNO would have invested in the hypothetical "counterfactual" situation in which it owned the same spectrum rights at the same time, but with different license durations (e.g., with all licences extended by, say, five years). Ideally, we would make this comparison separately for each period in the entire investment cycles of each network generation (e.g., 3G, 4G, etc.). Of course, such counterfactual data is never available in observational studies. Instead one needs to

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20 Note that we have neither EBITDA data, nor data on the years of incumbency of the different operators.

21 The Ookla® Speedtest® Intelligence data procured by Ofcom include average download and upload speeds at the operator level on a quarterly basis, broken down by technology type. The analysis presented in the present paper only utilises data on download speeds and, for the remaining of this paper, we will refer to this data as 'Ookla Download Speed Data'.

22 For Population, we take the annual population data and convert it to quarterly data.

estimate a counterfactual situation based on the available factual data and based on assumptions about the industry. However, any such estimation is made difficult by both the nature of this industry (hence of *any* data about it), which does not allow a neat separation of spectrum licenses and investments related to each network at each point of the investment cycle, and by other contingent limitations of the data available to us..

38. The first, and most difficult, problem in analysing the relationship between spectrum license duration and MNO's capital investment is that MNOs invest in networks that make an integrated use of a variety of spectrum rights, typically acquired at different times and with licenses of different durations. For example, an MNO may be investing in the upkeep of its 3G infrastructure, whose license may be expiring soon, while they build up their 4G network, which relies on a newly acquired license. However, the available capital expenditure data does not differentiate between investments related to the use of the spectrum corresponding to different licenses, hence it is not possible to identify directly the effects of individual license durations on operators' investment choices. More fundamentally, even restricting attention to a single network generation (to the extent that network can be thus separated), there often are still several licences whose spectrum is used in that network and whose impact on investment requirement is not merely additive, i.e., the utilization of the spectrum covered by one license may requires a level of capital investment that depends on the availability of the spectrum covered by the other licences.

39. The second problem is that the impact of different license durations is not necessarily constant and may instead be different at different points in the investment cycle of any given generation of mobile networks. For example, whether the license lasts for 20 or 15 years may not matter much for early investment, as the initial infrastructure is required early on in both cases. However, the investment incentives MNOs face in the 15th year of the license may differ significantly, as that would be the last year for which spectrum availability is guaranteed under the 15-year license while five more years would be guaranteed under the 20-year license (assuming, of course, that significant capital investment in the network is still needed at that time). More generally, the nature of mobile networks' investment cycles implies that investment levels at each point in time cannot be considered independently of previous investments in the same network, nor independently of the expectations about future investments by the same MNO. The fact that we only have aggregate (firm-level) data on capital investments for about ten years severely limits the analysis of these long-term effects.

40. The third major problem we face is that the effective duration of licenses is sometimes unclear. In some cases, licenses have been issued for a given fixed duration and have then been extended or renewed without undergoing a new selection process – and without the conditions for these extensions being clearly specified (or even mentioned) at the time of the original award. It is then difficult to establish when license holders became convinced that they would be able to keep their licenses beyond the original term and adjusted their investment plans accordingly. Even when the possibility of automatic renewal of the licenses was in the cards from the start, a judgement call must be made to decide whether there was sufficient certainty on this point to consider these licenses as having a *de facto* longer, or even indefinite, duration.[23]

23 The decisions on this point have been made in agreement with OFCOM's team. The presence of license with indefinite duration also creates some technical problems in that duration can no longer be considered a continuous variable. We discuss this issue in more detail in section 0

41. The difficulty of resolving all these problems simultaneously prevents the estimation of a single comprehensive model of this potential relationship between mobile spectrum license duration and MNOs' investment levels. We must therefore adopt a different approach to the empirical analysis – or, rather, adoption of a set of complementary approaches that look at this relationship from different angles.

42. We start by revisiting (in section 4.1) what is, to the best of our knowledge, the only previous work in the economic literature exploring the empirical relationship between investment and spectrum license duration, namely the JLL paper. After a discussion of JLL's methods and results, we conduct a similar analysis to check the robustness of their results to the use different sample periods and sets of countries (i.e., using the datasets described in the previous section) and to alternative model specifications, including the use of alternative measures of spectrum duration and investments.

43. We consider next (in section 0) whether a relationship between investments and license durations can be established at the country level, rather than at the operator level. More specifically, for each country in our dataset we take the quarters when a spectrum auction occurred and compare the average operators' investments in the next 1 to 5 years for different values of the average duration of the licenses awarded in that quarter.

44. We then return to analyses focused at the operator level. In section 4.3 we investigate the change in operators' investments in the two years following the award of a spectrum license compared to their level one year before the award. This "impulse response" analysis complements and differs from the cross-country analysis not only because it takes the individual operator (and not the country) as the level of observation is the operator, but also because we explicitly model the investment dynamics following the auction instead of a single, cumulative measure as in the cross-country analysis above.

45. Both analyses in section 0 and in section 4.3 focus on the first few years after the acquisition of a spectrum licence. However, the effects of license duration on investments may be felt more intensely in the later years of a license life. We investigate this in section 4.4 by computing operators' overall level of investments between the 11th and the 15th year of their 3G licenses and observing how this level differs between cases where the 3G license had a 15-year duration (hence these were the last five years of the license) and cases where it had a 20-year or indefinite duration (hence there were still another five or more years on the license to recoup the cost of these investments).

46. Finally, while investments are desirable, they are not an end goal in themselves. They mainly contribute to consumer welfare by allowing operators to offer higher quality service, namely broader coverage, higher transmission speed, lower latency, etc. In section 4.5 we investigate whether our data show a positive effect of investment on one specific measure of service quality (increases in average download speed in the transition from 3G to 4G) and whether, regardless of investment levels, this measure is correlated directly with license duration.

47. The discussions of these analyses below are mostly framed in causal terms: we interpret any correlation between licence duration and investments (or download speed) as indicative of a causal link from the former to the latter. Strictly speaking, this interpretation is not warranted since, in theory, the direction of causal effects may also run in the opposite direction, i.e., from (expected) investment levels post-auction to the duration of the licenses. This may occur if, for example, regulators choose the duration of license to be awarded in a given auction based on the maturity of the technology to be implemented or of the type of investment path that they expect (or they want to encourage) from winning bidders. For

example, they could issue licenses with longer duration when the technology for which the spectrum is to be used was still in its infancy or even not yet ready for deployment in the network; conversely they could choose licenses with shorter duration when they can reasonably expect winning bidders to put the spectrum to full use rather quickly anyway. The assessment of the extent to which regulators actually adopt such strategies in relation to mobile spectrum – and the impact of the corresponding reverse causation pathway on the estimates reported below – is beyond the scope of the this report.

4.1. A quarterly panel data analysis – testing the main implications of JLL

48. In this subsection we summarize the main results of JLL, followed by a detailed discussion of their approach. We assess the robustness of their results by extending their analysis in two ways: first, we use a distinct but similar sample; second, we use alternative specifications for some variables.

4.1.1. JLL's analysis

49. JLL aim to empirically assess the relationship between mobile spectrum license duration and operators' investment. To do so, they combine data on license duration, per capita CAPEX, and other control variables for 14 countries over a 10-year period to estimate the determinants of per capita CAPEX, and in particular the effect of increased license durations. The analysis exploits the panel structure of the data across time, countries, and operators.

50. While they use a battery of specifications, their main model regresses per capita CAPEX on mean spectrum license duration among all the operators' licenses, controlling for other factors such as the number of operators in a country, MVNO share, HHI, population density, GDP per capita, Mobile Termination Rates, as well as operator and time fixed effects. The authors find a statistically significant relationship between per capita CAPEX and the mean license duration both when controlling and not controlling for the different variables, indicating that a 1-year increase in the average license duration is associated with an increase of EUR 0.37-0.40 in per capita CAPEX by an operator, or about 3% of the average per capita CAPEX in their sample (EUR 13.25).

51. JLL proceed to estimate a second set of specifications that regress per capita CAPEX on the duration of the most recently acquired license.[24] This is because each new license requires some new investment, so the duration of the most recent one may be more relevant than the average duration. They find again a statistically significant and positive correlation between per capita CAPEX and this duration variable which is even higher in magnitude. Here, for a 1-year increase in the duration of the most recent license they estimate an associated increase of EUR 0.87-1.25 in per capita CAPEX, or about 8% of the average per capita CAPEX in their sample.

52. The authors further estimate additional regressions that estimate the effect of license duration on a measure of competition (Lerner Index)[25] and a measure of concentration (HHI), finding that neither of those variables is statistically significantly correlated with

24 These specifications, however, do not account for operator or time fixed effects.

25 JLL use as measure of the Lerner index 1-EBITDA/Revenue for this robustness check. Note that in our data information on EBITDA data is not available. Also note that EBITDA margin, i.e. EBITDA/Revenue, does not include cost of capital investments or interest expenses but is rather a simple measure of the firms' operating profit.

license duration. This leads the authors to conclude that higher spectrum license duration increases per capita capital investment without adverse impacts on competition.

4.1.2. A critical review of JLL's approach

53. JLL to our knowledge is the first paper to empirically approach the relationship between spectrum license duration and per capita investment in detail. The main approach is a panel analysis that focuses on the determinants of quarterly per capita investment across different countries and network operators. Unfortunately, there are several aspects of the JLL approach that limit its ability to identify and adequately estimate the relationship between investments and licence durations.[26]

54. One particular challenge related to the industry is that most operators have overlapping licenses for spectrum that is used in network of different generations and that thus find themselves, at each point in time, in a different phase of the corresponding network investment cycles – but the available data do not disaggregate the operators' CAPEX on the basis of the network and spectrum licences it relates to. JLL address this aggregation problem in two different ways. The first of the JLL specifications, which regresses per capita CAPEX on the mean spectrum duration of all licenses, implicitly assumes that all the licenses (and their durations) have the same impact on investment. The second specification goes into the opposite direction by focussing exclusively on the last licences acquired by the operators, thus implicitly assuming that all other licenses have no systematic impact on investments (or, more precisely, that any such impact is independent of the impact from the last licences to be acquired).[27]

55. While potentially useful as part of a broader analysis, neither of these assumptions are likely to hold in reality, nor can they be considered as polar cases that "bracket" the true impact of licence durations on investment. Moreover, the implementation of these approaches in JLL is particularly problematic for two reasons. First, to compute the duration measures, JLL use the initial number of years of a license instead of the remaining years at a given time, e.g., a license originally awarded for 20 years is still considered as 20-year licence even if was awarded 15 years before and has only five years left before expiration. But investment is forward-looking, so the remaining years of a licence (i.e., just five years in the previous example) should be a more important determinant. Second, none of the JLL specifications compare investments at the same time in the investment cycle (e.g., 1, 5 or 10 years after having acquired the license) even though a network built around an older license has typically already benefited from extensive investments compared to a newer one and may also be already in the process of being replaced by a network of a newer

26 As for any regression analysis, a key question is whether the statistical correlations between the dependent variable (per capita CAPEX) and the various independent variables included in the analysis (notably, licence durations) can be given a causal interpretation. In principle, this is not guaranteed as, for example, regulators in each country may have chosen certain licence durations in response to specific features of investment behaviour in their country. However, our understanding is that regulators have typically chosen license durations on the basis of rather general intuitions about investment implications and that this type of reverse causation is unlikely to cause any significant bias in the analysis.

27 Essentially, the other licences (and their durations) are omitted variables in this regression, so the question is whether the omission introduces a significant bias with respect to the included duration variable.

generation. Relatedly, JLL's analysis largely ignores specificities of different technologies, i.e., treating 3G, 4G, and 5G licenses the same for the main specifications.[28]

There are also some other more technical aspects of the JLL approach that warrant the further discussion below.

Computations of standard errors

56. JLL use standard errors that account for heteroskedasticity but assume that observations are uncorrelated. We believe a more conservative approach is advisable here, because CAPEX per capita are likely to be correlated within a country or for an operator at different points in time. Assuming otherwise would underestimate the level of uncertainty in the data. For this reason, we believe it necessary to cluster standard errors as this allows for errors within a cluster to be correlated. We choose the cluster to be the operator, but the statistical significance of the results remains relatively comparable if we cluster on a country-level instead.

57. Moreover, when looking at the specification that considers only the last licences acquired by the operators, JLL do not include any fixed effects on country, operator, or quarter level as additional regressors. Such fixed effects could pick up differences across operators or time that are correlated with the duration of the last acquired license, and that could affect the importance (both in magnitude and significance) of the license duration variable.

Computation of per capita CAPEX variable

58. JLL define the per capita CAPEX variable as the operator's CAPEX divided by the product of the country's total population and the operator's market share in the country. This base differs from the quarterly number of subscribers for each operator at a given quarter, which is also available data and might be more precise. For this reason, we also estimate the models under this alternative per capita CAPEX measure, i.e., total quarterly CAPEX of an operator divided by the number of this operator's subscribers at the same time.

4.1.3. Definition of the relevant variables

59. We next provide an explanation of how we construct the variables used when applying our data to the empirical modelling of JLL and in the alternative specifications of JLL's approach that we have considered. This is followed by a further discussion of how these variables differ in some cases from those in JLL.

Main generation of the data

- **License duration.** JLL use mean license duration and duration of the last license as license duration measures, always based on the total initial license duration.[29] We calculate these license durations in two different ways.

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28 In Table A-1 in the Appendix, JLL test for differences in the impact of the latest license duration on per capita investment depending on the frequency band. However, this analysis does again not account for differences in the timing cycles.

29 These mean durations are computed as simple means of license durations, without weighting them, e.g. by how many MHz of spectrum they cover.

- First, we calculate *full* duration measures by using initial license duration as is also done by JLL. The mean full duration captures the average initial investment horizon for an operator's different licenses. The last license full duration measure captures the initial license duration of an operator's last acquired license. Using the initial license duration does not account for the fact that older licenses have already a lower duration, which should reduce the incentive to invest in them.
- Second, we compute the *remaining* duration measurers of active licenses at any given quarter.[30] The mean remaining license duration measure will be dampened down by licenses with a low remaining duration while at the same time those licenses might also be given little weight in terms of capital investment anyway. This is not the case by the remaining last license duration measure, which we believe to be a preferable measure for this reason.

- **CAPEX per subscriber.** We calculate per capita CAPEX in two different ways. First, as JLL, we calculate CAPEX per capita by using an operator's total CAPEX divided by a population weight that is computed as the total population times the operator's revenue share in the country. We further calculate CAPEX per subscriber by dividing the total CAPEX by the number of subscribers, both of which come from the OMDIA WCIS dataset.[31]
- **GDP per capita.** The GDP per capita is quarterly data from the OECD database, adjusted for seasonality and PPP.[32]
- **Population density.** Population density is computed as quarterly/annual population data divided by country area (in square km).
- **Mobile Termination Rates (MTR).** We compute the MTRs per minute for each country using WCIS Interconnect Benchmark data.
- **Sequence of entry.** JLL have available data on the years of incumbency from the Telecom Matrix database. For our version of the Telecom Matrix database, however, this data is not available anymore. Instead, we make use of a variable from the same database that tracks whether an operator has been one of the first entrants in the market (i.e., first or second), or a later entrant. While this does not cover the age of an operator, it can still cover relative age differences between operators in a country. Specifically, we use "a longevity dummy", for which we set the value to 0 for the first and second entrants and to 1 for all other entrants.
- **Number of active MNOs.** This number is computed using the active number of mobile operators from the WCIS data.

30 In case a license has a total duration of 15 years but is already active for 7 years, the remaining duration variable will count this license as 8 years, while the other total license will count it as 15 years.

31 We have removed outliers for CAPEX – in the data we see 7 observations with CAPEX per subscriber more than 10 times higher than the average, and we remove the 2l CAPEX per subscriber values above 400. When calculating CAPEX per subscriber by dividing CAPEX by subscribers, we remove the 18 CAPEX per subscriber values above 135.

32 For Turkey, this data is not available and GDP per capita is computed using annual World Bank data instead, adjusted for PPP.

- **HHI.** We calculate this concentration measure using annual WCIS as the sum of squared subscription shares for all operators. The shares are calculated on a yearly level to harmonize out some outliers with missing quarterly subscription data.[33]
- **MVNO shares.** We compute the quarterly connection share of Mobile Virtual Network Operators (MVNOs) in a given month and country using Telecom Matrix data.

60. Besides the baseline set of 14 countries also included in JLL, we provide two additional sets of countries. One covers the full list of EU countries plus the UK. The second covers all EU countries and Australia, Canada, Chile, Colombia, Costa Rica, Iceland, Israel, Japan, Mexico, New Zealand, Norway, South Korea, Switzerland, Turkey, UK, USA. Table 1 below provides summary statistics of the main variables for the three different sets of countries used in our estimations. These summary statistics suggests that the different variables are broadly comparable to those of JLL. The mean CAPEX per capita is greater (EUR 16.4 vs EUR 13.3 in JLL) in our data, which could be explained by both inflation and increased demand. The mean license duration variables (17.7 years vs 17.9 years in JLL) and last license duration variable (18.0 years vs 19.3 years in JLL) are very close.

Table 1: Summary statistics for selected variables

Baseline set of 14 countries as in JLL:

	count	mean	sd	min	max
Capex pc 2	1947	16.41276	13.20174	1.025517	261.9112
Mean duration, full duration	1754	17.76345	1.909352	13.77778	21.66667
Mean duration, remaining duration	1754	11.48315	3.646517	.25	20.75
GDP per capita, in euros	1947	40099.25	9902.054	18692.13	65893.32
Population density	1947	165.1496	133.1864	13.50012	520.8197
Mobile Termination Rate, in euros	1455	1.818194	1.466097	.1649349	9.03566
Later entrant	1947	.3954802	.4890792	0	1
HHI	1947	.3337176	.0516395	.2811696	.5084757
MVNO share measure	1947	.0995164	.0703607	.0022	.3001
Duration of last license	1751	18.02964	2.789122	10	25

EU countries+UK:

	count	mean	sd	min	max
Capex pc 2	3550	10.76247	9.216025	.1217649	261.9112
Mean duration, full duration	2986	16.77436	2.757229	5	21.66667
Mean duration, remaining duration	2986	10.99176	3.609311	.25	20.75
GDP per capita, in euros	3421	32569.54	11752.83	10883.58	92340.51
Population density	3550	126.8495	106.444	17.69545	520.8197
Mobile Termination Rate, in euros	2455	1.905394	1.476791	.1649349	9.269593
Later entrant	3550	.4211268	.4938094	0	1
HHI	3550	.3303754	.0358933	.2506315	.4451294
MVNO share measure	3550	.0597397	.0658746	0	.3001
Duration of last license	2980	16.56143	3.633172	5	25

All countries:

33 The results do not change qualitatively when instead computing HHI based on the number of connections per operator.

	count	mean	sd	min	max
Capex pc 2	3803	12.22729	11.90282	.1217649	261.9112
Mean duration, full duration	3173	16.70871	2.693057	5	21.66667
Mean duration, remaining duration	3173	10.848	3.72952	.25	20.75
GDP per capita, in euros	3674	34084.5	12755.96	10883.58	92340.51
Population density	3803	125.8107	105.9885	13.50012	520.8197
Mobile Termination Rate, in euros	2645	2.009738	1.600397	.1649349	9.269593
HHI	3803	.3381614	.0458918	.2506315	.5084757
MVNO share measure	3803	.0632933	.0657027	0	.3001
Duration of last license	3164	16.55233	3.549254	5	25

Source: CRA Analysis.

Data differences compared to JLL

61. While our specifications are relatively close to those in JLL, there are still several differences that are worthwhile highlighting.

- Timing and use of data: Our timing differs as the number of observations per country is higher compared to JLL's because of the longer timeframe that we look at (2011Q1 -2021Q1 compared to 2008Q2 to 2017Q3 in JLL).
- The main reason for our analysis only starting in 2011Q1 is that OMDIA highlighted worries about the quality of the earlier operator CAPEX data, which is why such data was not available to us. Note that the analysis in JLL relies on such OMDIA CAPEX data over this earlier period.
- Incumbency data vs longevity dummy: We use a different variable to measure seniority of an operator in a country, as discussed above.

4.1.4. Estimation results

62. We next conduct similar approaches as JLL to test the robustness of their results with our dataset. This includes testing whether the qualitative results remain when we expand the list of countries or change either the dependent variable's definition or the definition of the duration measure. The estimation equation for the per capita CAPEX of operator *e* in country *c* at time *t* for the first specification can be written as:

$$CAPEX\_pc_{it} = c + \alpha \, \mathrm{d}uration\_mean_{it} + \beta X_{it} + \gamma Y_{ct} + T_t + M_i + \epsilon_{it}.$$

Here c is a constant, $\mathrm{d}uration\_mean_{it}$ is the mean duration of all of operators *i*'s licenses that are active at time *t*. Depending on the relevant specification, X_{it} includes control variables on an operator level such as whether the operator is an early or late entrant, and MTR, while Y_{ct} contains country-specific data at a given time such as GDP per capita, population density, Mobile Termination Rates, the later entrant dummy variable, number of firms, HHI, and MVNO market share. Moreover, the estimation also accounts for operator fixed effects M_i, and for quarter fixed effects T_t.

63. The second specification replaces the mean license duration with the duration of the last license, while neither accounting for quarter nor operator fixed effects to follow JLL:

$$CAPEX\_pc_{it} = c + \alpha \, \mathrm{d}uration\_lastlic_{it} + \beta X_{it} + \gamma Y_{ct} + \epsilon_{it}.$$

Baseline estimations

64. Table 2 shows the results for the first specification that uses mean duration licenses and includes quarter and operator fixed effects for the same countries as JLL. Unlike JLL, we

see a *negative* rather than a positive and statistically significant relationship between mean duration and per capita CAPEX. Moreover, nearly all other covariates (excluding fixed effects) are not statistically significant on a 95% percent significance level for all specifications. We next explain the interpretation of the different coefficients in these regressions. Each coefficient reflects by how much (in EUR) per capita CAPEX would change with a unit increase in the specific explanatory variable. For example, a coefficient of -0.84 for mean duration in variant (7) indicates that a 1-year increase in the mean license duration is associated with a decrease of EUR 0.84 in per capita CAPEX by an operator (i.e., a 5% reduction), controlling for all other factors. At the same time, if HHI changes by 0.1, per capita CAPEX would change by 0.1*EUR 1.63= EUR 0.163, indicating a higher per capita CAPEX for countries with higher concentration. However, this variable is statistically insignificant, so one cannot reject the hypothesis that the effect of this variable is exactly 0. The (weakly significant) 0.81 MTR coefficient suggests that a EUR 0.01 increase in MTR would be associated with a per capita CAPEX that is EUR 0.008 higher, controlling for all other factors. The variable later entrant captures the difference per capita CAPEX between later entrants and earlier entrants. Here a positive coefficient of 6.11 suggests that controlling for all other effects, later entrants have a per capita CAPEX that is EUR 6.11 higher than earlier entrants. However, this effect is again statistically insignificant – the high standard error of this variable suggests huge variation in the investment behaviour among different early and late entering MNOs in this case.

Table 2: Full mean duration estimations for the 14 baseline countries

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Mean duration, full duration	-0.67**	-0.80*	-0.76**	-0.76**	-0.83***	-0.83***	-0.84***
	(0.31)	(0.43)	(0.31)	(0.31)	(0.30)	(0.29)	(0.29)
GDP per capita, in euros	0.00026	0.00015	-0.0000032	-0.0000032	-0.000043	-0.000034	-0.000015
	(0.00023)	(0.00027)	(0.00024)	(0.00024)	(0.00024)	(0.00023)	(0.00023)
Population density		0.12	0.078	0.078	0.064	0.061	0.047
		(0.20)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)
Mobile Termination Rate, in euros			0.71	0.71	0.77	0.76	0.81*
			(0.47)	(0.47)	(0.47)	(0.47)	(0.47)
Later entrant				10.5	7.43	6.61	6.11
				(22.5)	(22.7)	(22.1)	(22.6)
Number of MNOs					-1.27*	-0.88	
					(0.64)	(0.70)	
HHI						11.8	16.3
						(13.6)	(12.5)
MVNO share measure							14.5
							(8.71)
Adj. R-Square	0.54	0.54	0.54	0.54	0.54	0.54	0.54
No. obs.	1754	1754	1301	1301	1301	1301	1301
No. clusters	48	48	48	48	48	48	48
Operator and Quarterly fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: CRA Analysis. Standard errors clustered at the operator level.

65. Table 3 focuses on the second specification that includes the total duration of the last licenses (while not including country or operator fixed effects). None of the duration-of-last-license coefficients are statistically significant, however, many of the other covariates such as GDP per capita, MTR, and HHI become statistically significant.

Table 3: Full last license duration estimations for the 14 baseline countries

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Duration of last license, full duration	-0.23	-0.25	0.060	0.053	0.063	0.13	0.13
	(0.20)	(0.20)	(0.14)	(0.13)	(0.12)	(0.12)	(0.12)
GDP per capita, in euros	0.00031***	0.00032***	0.00030***	0.00031***	0.00028***	0.00018***	0.00017***
	(0.000096)	(0.000094)	(0.000064)	(0.000065)	(0.000066)	(0.000061)	(0.000062)
Population density		-0.0084*	-0.0086**	-0.0087**	-0.0079**	-0.0074*	-0.0090*
		(0.0043)	(0.0037)	(0.0038)	(0.0039)	(0.0040)	(0.0052)
Mobile Termination Rate, in euros			2.09***	2.14***	2.02***	1.48***	1.52***
			(0.48)	(0.48)	(0.47)	(0.45)	(0.45)
Later entrant				0.84	1.12	1.52	1.73
				(1.18)	(1.17)	(1.13)	(1.17)
Number of MNOs					-1.51	2.59**	
					(1.01)	(1.05)	
HHI						71.8***	52.0***
						(15.7)	(12.2)
MVNO share measure							6.32
							(9.74)
Adj. R-Square	0.098	0.11	0.22	0.22	0.23	0.28	0.28
No. obs.	1751	1751	1298	1298	1298	1298	1298
No. clusters	48	48	48	48	48	48	48
Operator and Quarterly fixed effects	No	No	No	No	No	No	No

Source: CRA Analysis. Standard errors clustered at the operator level.

Remaining license duration results

66. As discussed above, we do not believe that the *total* spectrum license duration is the most appropriate measure to assess the impact of license duration on capital investment. A more intuitive measure is the *remaining* license duration, as it accounts for the time left for an operator to monetise a spectrum license. We next use remaining duration measures, first focusing again on the 14 JLL countries.

67. Table 4 shows the regression results for the first specification with mean remaining license durations. For this specification, we indeed find a statistically significant relationship between per capita CAPEX and the remaining duration for most variants. The magnitude of the duration coefficient suggests that when controlling for all other factors, an additional year of mean remaining license duration is associated with an additional per capita CAPEX of between EUR 0.31- EUR 0.45, which is of a similar magnitude as JLL find for their mean full duration specification. This positive relationship is not statistically significant (and of lower magnitude), however, when using the remaining last license duration measure as shown in Table 5**Error! Reference source not found.**.

Table 4: Remaining mean duration estimations for the 14 baseline countries

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Mean duration, remaining duration	0.38	0.45*	0.33**	0.33**	0.33**	0.32**	0.31*
	(0.24)	(0.25)	(0.15)	(0.15)	(0.15)	(0.15)	(0.16)
GDP per capita, in euros	0.00022	0.00036	0.00019	0.00019	0.00017	0.00017	0.00018
	(0.00021)	(0.00026)	(0.00023)	(0.00023)	(0.00023)	(0.00023)	(0.00023)
Population density		-0.17	-0.16	-0.16	-0.17	-0.17	-0.18
		(0.16)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)
Mobile Termination Rate, in euros			0.66	0.66	0.68	0.67	0.70
			(0.45)	(0.45)	(0.45)	(0.45)	(0.45)
Later entrant				-28.0	-30.1	-30.1	-29.4
				(22.5)	(22.8)	(22.7)	(22.9)
Number of MNOs					-0.77	-0.60	
					(0.58)	(0.69)	
HHI						5.29	8.67
						(15.4)	(13.5)
MVNO share measure							9.66
							(9.11)
Adj. R-Square	0.55	0.55	0.54	0.54	0.54	0.54	0.54
No. obs.	1754	1754	1301	1301	1301	1301	1301
No. clusters	48	48	48	48	48	48	48
Operator and Quarterly fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: CRA Analysis. Standard errors clustered at the operator level.

Table 5: Remaining mean duration estimations for the 14 baseline countries

	(1) Capex pc 1	(2) Capex pc 1	(3) Capex pc 1	(4) Capex pc 1	(5) Capex pc 1	(6) Capex pc 1	(7) Capex pc 1
Duration of last license, remaining duration	0.028	0.030	0.13*	0.11	0.100	0.092	0.082
	(0.12)	(0.12)	(0.075)	(0.086)	(0.081)	(0.068)	(0.068)
GDP per capita, in euros	0.00015**	0.00015**	0.00016***	0.00017***	0.00015***	0.000043	0.000036
	(0.000067)	(0.000067)	(0.000055)	(0.000056)	(0.000054)	(0.000044)	(0.000046)
Population density		-0.00021	-0.000027	-0.000057	0.00042	0.00073	-0.00050
		(0.0033)	(0.0033)	(0.0034)	(0.0034)	(0.0033)	(0.0044)
Mobile Termination Rate, in euros			1.46***	1.47***	1.39***	0.82**	0.85***
			(0.36)	(0.36)	(0.34)	(0.32)	(0.31)
Later entrant				0.19	0.36	0.78	1.02
				(0.96)	(0.96)	(0.83)	(0.92)
Number of MNOs					-0.93	3.17***	
					(0.88)	(0.96)	
HHI						71.6***	47.3***
						(14.4)	(9.47)
MVNO share measure							5.69
							(9.41)
Adj. R-Square	0.046	0.046	0.14	0.15	0.15	0.26	0.23
No. obs.	1875	1865	1383	1298	1298	1298	1298
No. clusters	52	52	52	48	48	48	48
Operator and Quarterly fixed effects	No	No	No	No	No	No	No

Source: CRA Analysis. Standard errors clustered at the operator level.

Extending the number of countries

68. We next extend the analysis to a wider number of countries. Table 6 and Table 7 show the mean and last remaining license duration specifications for all EU countries plus the UK. For the mean remaining duration estimations in Table 6, the different variants lead to no or only a weakly statistically significant positive relationship between license duration and per capita CAPEX. The magnitude of the duration effect is also smaller than for the 14 baseline countries, with the only two variants with (weakly) statistically significant effects (variants (3) and (4) in Table 6) suggesting that an additional year of duration for the average license is associated with an increase in per capita CAPEX of EUR 0.15, or about 1.4% of the average per capita CAPEX in this sample. This is again different when looking at the last remaining license duration estimations in Table 7, for which there is a positive and statistically significant relationship. The magnitude of the coefficients here suggests that an additional year of the last remaining duration is associated with a higher per capita CAPEX of between EUR 0.23 - EUR 0.28, or about 2.1-2.6%, when controlling for all other factors. Note that this, while still sizeable, is only roughly one fourth of the magnitude of EUR 0.87-EUR 1.25 that JLL find for their full last license specification for their 14 countries.

Table 6: Remaining mean duration estimations, all EU countries + the UK

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Mean duration, remaining duration	0.080	0.094	0.15*	0.15*	0.14	0.14	0.11
	(0.073)	(0.075)	(0.084)	(0.084)	(0.084)	(0.088)	(0.093)
GDP per capita, in euros	0.000044	0.000063	0.000054	0.000054	0.000042	0.000012	0.0000069
	(0.00011)	(0.00012)	(0.00011)	(0.00011)	(0.00011)	(0.00011)	(0.00011)
Population density		-0.079	-0.15	-0.15	-0.16*	-0.14	-0.15
		(0.099)	(0.093)	(0.093)	(0.094)	(0.093)	(0.094)
Mobile Termination Rate, in euros			0.67*	0.67*	0.67*	0.71**	0.73**
			(0.35)	(0.35)	(0.35)	(0.34)	(0.34)
Later entrant				7.87***	8.40***	9.93***	9.67***
				(2.45)	(2.60)	(2.66)	(2.65)
Number of MNOs					-0.53	0.13	
					(0.44)	(0.44)	
HHI						26.4**	22.4**
						(12.0)	(10.8)
MVNO share measure							10.3
							(8.10)
Adj. R-Square	0.51	0.51	0.48	0.48	0.48	0.48	0.49
No. obs.	2903	2903	2021	2021	2021	2021	2021
No. clusters	83	83	83	83	83	83	83
Operator and Quarterly fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: CRA Analysis. Standard errors clustered at the operator level.

Table 7: Remaining last license duration estimations, all EU countries + the UK

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Duration of last license, remaining duration	0.23***	0.23***	0.26***	0.26***	0.27***	0.28***	0.24***
	(0.077)	(0.079)	(0.071)	(0.068)	(0.066)	(0.065)	(0.068)
GDP per capita, in euros	0.00022***	0.00022***	0.00024***	0.00024***	0.00025***	0.00026***	0.00021***
	(0.000036)	(0.000037)	(0.000035)	(0.000033)	(0.000034)	(0.000034)	(0.000036)
Population density		0.000079	0.00075	0.00086	-0.000061	-0.00032	-0.0042
		(0.0039)	(0.0035)	(0.0037)	(0.0038)	(0.0039)	(0.0052)
Mobile Termination Rate, in euros			0.19	0.21	0.29	0.31	0.19
			(0.32)	(0.32)	(0.29)	(0.28)	(0.32)
Later entrant				1.71*	1.58*	1.57*	1.79**
				(0.89)	(0.87)	(0.87)	(0.87)
Number of MNOs					1.23	2.30**	
					(0.78)	(1.03)	
HHI						21.9	6.90
						(13.9)	(11.7)
MVNO share measure							13.5
							(9.62)
Adj. R-Square	0.12	0.12	0.14	0.16	0.16	0.17	0.16
No. obs.	2897	2897	2017	2017	2017	2017	2017
No. clusters	83	83	83	83	83	83	83
Operator and Quarterly fixed effects	No	No	No	No	No	No	No

Source: CRA Analysis. Standard errors clustered at the operator level.

69. Table 8 and Table 9 show similar analyses including also non-EU OECD countries. For this set of countries, the relationship between license duration and per capita investment is generally positive but only weakly statistically significant for a few variants. The magnitude of the license duration effect is comparable to before, with an additional remaining year of duration being associated with an additional per capita CAPEX of between EUR 0.17 – EUR 0.21, or about 1.4-1.7% of the average per capita CAPEX in the sample, for the weakly significant variants.

Table 8: Remaining mean duration estimations, all countries

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Mean duration, remaining duration	0.23	0.24	0.21*	0.21*	0.20*	0.20*	0.18*
	(0.16)	(0.15)	(0.10)	(0.10)	(0.10)	(0.10)	(0.11)
GDP per capita, in euros	0.000072	0.000075	0.000057	0.000057	0.000050	0.000036	0.000029
	(0.00012)	(0.00013)	(0.00011)	(0.00011)	(0.00011)	(0.00011)	(0.00011)
Population density		-0.012	-0.12	-0.12	-0.12	-0.12	-0.12
		(0.12)	(0.092)	(0.092)	(0.093)	(0.092)	(0.094)
Mobile Termination Rate, in euros			0.68**	0.68**	0.68**	0.68**	0.70**
			(0.33)	(0.33)	(0.33)	(0.33)	(0.33)
Later entrant				7.16***	7.49***	8.41***	8.12***
				(2.30)	(2.40)	(2.58)	(2.62)
Number of MNOs					-0.36	-0.038	
					(0.43)	(0.44)	
HHI						14.3	12.8
						(11.8)	(10.9)
MVNO share measure							10.6
							(8.01)
Adj. R-Square	0.57	0.57	0.56	0.56	0.56	0.56	0.56
No. obs.	3090	3090	2161	2161	2161	2161	2161
No. clusters	89	89	89	89	89	89	89
Operator and Quarterly fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: CRA Analysis. Standard errors clustered at the operator level.

Table 9: Remaining last license duration estimations, all countries

	(1) Capex pc 2	(2) Capex pc 2	(3) Capex pc 2	(4) Capex pc 2	(5) Capex pc 2	(6) Capex pc 2	(7) Capex pc 2
Duration of last license, remaining duration	0.071	0.073	0.13	0.13	0.13	0.17**	0.12
	(0.11)	(0.12)	(0.089)	(0.088)	(0.088)	(0.080)	(0.082)
GDP per capita, in euros	0.00034***	0.00034***	0.00038***	0.00038***	0.00039***	0.00037***	0.00030***
	(0.000059)	(0.000059)	(0.000053)	(0.000053)	(0.000052)	(0.000046)	(0.000050)
Population density		-0.0012	-0.0011	-0.0011	-0.0014	-0.00045	-0.0071
		(0.0046)	(0.0041)	(0.0042)	(0.0043)	(0.0046)	(0.0058)
Mobile Termination Rate, in euros			1.35***	1.39***	1.41***	1.25***	1.09**
			(0.48)	(0.48)	(0.46)	(0.39)	(0.42)
Later entrant				0.94	0.90	1.14	1.44
				(0.96)	(0.95)	(0.94)	(0.95)
Number of MNOs					0.28	3.00***	
					(0.82)	(0.97)	
HHI						48.8***	31.9***
						(10.7)	(9.09)
MVNO share measure							21.3*
							(11.9)
Adj. R-Square	0.19	0.19	0.24	0.24	0.24	0.28	0.27
No. obs.	3081	3081	2154	2154	2154	2154	2154
No. clusters	89	89	89	89	89	89	89
Operator and Quarterly fixed effects	No	No	No	No	No	No	No

Source: CRA Analysis. Standard errors clustered at the operator level.

Robustness checks summaries and concluding discussions

70. Table 10 summarizes the relationship between mean license duration and per capita investment for different definitions of per-capita investments (as indicated in the first column "Investment Measure"), whether the mean duration measure captures the mean total duration or the mean remaining duration (as indicated in the second column "Mean Duration type"), and for the different regions, i.e. the 14 baseline countries that are also included in JLL, all EU countries plus the UK, and all OECD countries. The "Per capita CAPEX" investment measure uses JLL's definition of per capita CAPEX as the operator's CAPEX divided by the product of its market share and the country's population. The "Per subscriber CAPEX" investment measure instead uses the operator's CAPEX divided by the number of its subscribers. The results show that evidence of a positive correlation between the mean duration measures and per capita investment is at best mixed. There are some indications that the remaining license duration is indeed positively correlated with per capita CAPEX. However, here we have to caution that given that we have tested a plethora of models, the conventional t-statistics do not apply: given that statistical significance of the duration variables (as the variables of interest) in each model is falsely not rejected with a positive probability, the probability of falsely finding some significant relationship between these variables and the dependent per capita CAPEX variables increases with the number of variants tested.

71. Table 11 further presents the results for similar estimations for the impact of the duration of the last acquired license, including specifications that account for fixed effects (by operator and by year) as in the analysis of the impact of mean license duration.[34] Here again the evidence seems to be mixed at best – and highly sensitive to the specification used.

72. Overall, we do not find the clear positive relationship between license duration and per capita investment as JLL using our data. This can be because of different reasons as explained above, such as relying on data from different periods, differences in the quality

34 JLL accounted for fixed effects in their analyses of mean licence duration, but not those for the duration of the last acquired license.

of the WCIS data, slightly different specifications, and computation of standard errors. For most of our specifications which lead to a positive and statistically significant relationship between per capita CAPEX and the specific duration measure, the magnitude of the effect is substantially lower than the one found in JLL for their data.

Table 10: Summary matrix of estimates for the impact of average license duration

CAPEX measure	Duration Type	Region	Statistically significant and positive
Per capita	Full	JLL 14 countries	No
Per subscriber	Full	JLL 14 countries	No
Per capita	Remaining	JLL 14 countries	For some variants (but not consistently and at best at the 95% level)
Per subscriber	Remaining	JLL 14 countries	Yes
Per capita	Full	EU	No
Per subscriber	Full	EU	No
Per capita	Remaining	EU	For some variants (but not consistently and at best at the 90% level)
Per subscriber	Remaining	EU	For some variants (but not consistently and at best at the 95% level)
Per capita	Full	All	No
Per subscriber	Full	All	No
Per capita	Remaining	All	For some variants (but not consistently and at best at the 90% level)
Per subscriber	Remaining	All	Yes (at best at the 95% level)

Source: CRA Analysis

Notes: "Per capita CAPEX" is defined as the operator's CAPEX divided by the product of its market share and the country's population; "Per subscriber CAPEX" is the operator's CAPEX divided by the number of its subscribers. The duration type refers to computing duration always using the full initial duration at the beginning of the license, while remaining refers to computing the remaining duration of the license. The region "EU" also includes the UK. In all estimations, standard errors are clustered at the operator level.

Robustness checks regressions using last license duration variables

Table 11: Summary matrix of estimates for the impact of duration of the last acquired license

CAPEX measure	Duration Type	Region	Statistically significant and positive (without fixed effects)	Statistically significant and positive (with fixed effects)
Per capita	Full	JLL 14 countries	No	No
Per subscriber	Full	JLL 14 countries	For some variants (but not consistently and at best at the 90% level)	No
Per capita	Remaining	JLL 14 countries	No	For some variants (but not consistently and at best at the 90% level)
Per subscriber	Remaining	JLL 14 countries	No	For some variants (but not consistently and at best at the 99% level)
Per capita	Full	EU	For some variants (but not consistently and at best at the 95% level)	No
Per subscriber	Full	EU	For some variants (but not consistently and at best at the 95% level)	No
Per capita	Remaining	EU	Yes	No
Per subscriber	Remaining	EU	Yes	For some variants (but not consistently and at best at the 90% level)
Per capita	Full	All	For some variants (but not consistently and at best at the 95% level)	No
Per subscriber	Full	All	For some variants (but not consistently and at best at the 90% level)	No
Per capita	Remaining	All	For some variants (but not consistently and at best at the 95% level)	No
Per subscriber	Remaining	All	No	No

Source: CRA Analysis.

Notes: “Per capita CAPEX” is defined as the operator’s CAPEX divided by the product of its market share and the country’s population; “Per subscriber CAPEX” is the operator’s CAPEX divided by the number of its subscribers. The duration type refers to computing duration always using the full initial duration at the beginning of the license, while remaining refers to computing the remaining duration of the license. The region “EU” also includes the UK. In all estimations, standard errors are clustered at the operator level.

4.2. A country-level analysis

73. Operators' investments are typically not decided on a quarter-by-quarter basis, but reflect instead some coherent longer-term plan of network development which is adjusted to take into account of, *inter alia,* any new spectrum licence acquired (or renewed) by the operator. Consistently with this, the analyses in the rest of this section 4 focus on the impact of specific sets of licences on the subsequent investments at different points of the licence life.

74. Since license durations are typically the same for all operators in the same country – and often the same for all mobile spectrum – it makes sense to begin by investigating whether a relationship between investments and license durations can be established at the country level.

75. More specifically, for each country in our dataset we consider the quarters when a spectrum auction occurred and compare the average operators' investments in the first 1 to 5 years following each auction for different values of the average duration of the licenses. We provide more details on these variables below.

76. We emphasize that this aggregated analysis is just an initial exploration of the relation between investments and license duration. It mainly serves the purpose of providing an overview of the range of license durations chosen by different countries at different times and the corresponding levels of investments. While this summary of the data is useful, it also overlooks much of the heterogeneity at the operator level, i.e., at level where investment decisions are ultimately made, which is the focus of the later sections of this report.

77. We begin by providing more details on the variables considered in this analysis. First, in regard to average license durations, we find that there is indeed little variation among the licenses awarded in the same quarter in a given country. Out of the 184 unique country-quarters with auctions for which we have duration information, 168 have a unique duration for their licenses, even though only 31 country-quarters contain a single auction. For our subsample with CAPEX per capita information available for first 5 years after the auction (as explained below), there are 61 unique country-quarters, and 55 have unique license durations, even though only 11 country-quarters contain a single auction. For the remaining 6 country-quarters, we take the simple (unweighted) average of the duration of the corresponding licenses.

78. Second, we compute the average operator's investment in a country as follows. For each operator, we calculate its "per capita" CAPEX in each quarter as in the previous section and in JLL, i.e., as CAPEX divided by the product of the country's population and the operator's market share.[35] Then, we accumulate this CAPEX per capita over different time horizons, starting at the quarter in which the auction happens. Finally, we define a quarter-

35 The removal of outliers is important here not to distort the estimates. We removed from the sample the Slovenian operator Slovenij Telekom, the Turkish operator Turkcell, and the Dutch Tele 2. They won auctions when they had very few subscriptions (and hence small market share), but already had significant levels of CAPEX. Therefore, their CAPEX per capita is much higher than the rest of the sample (often by more than a factor of 20) and including them in the analysis would distort any average that encompassed them.

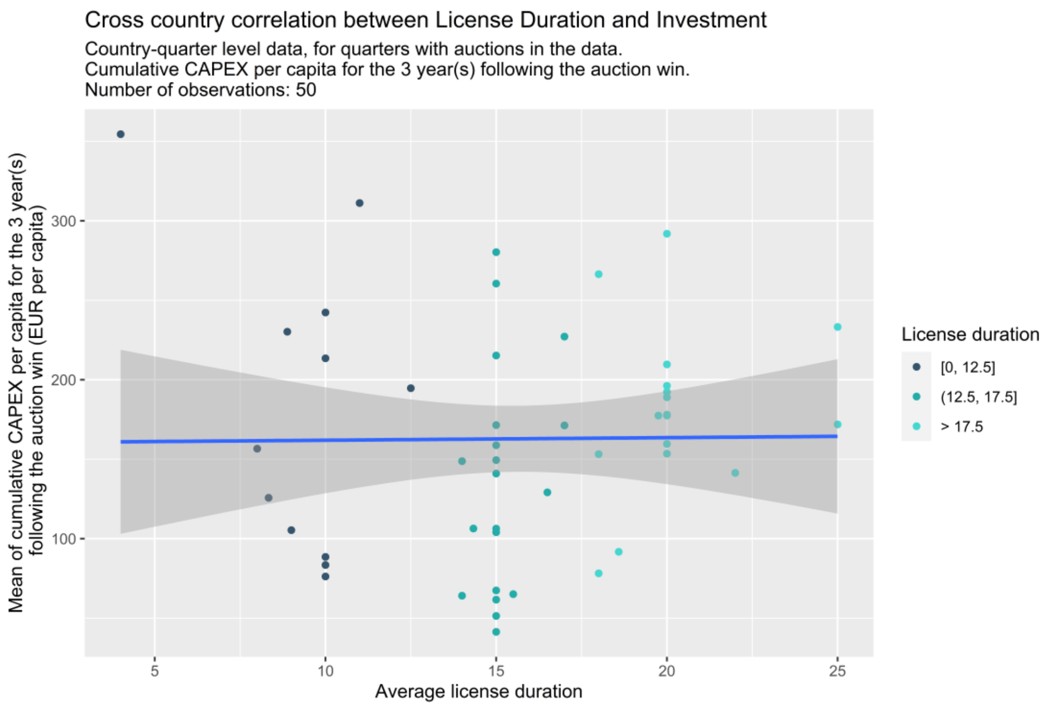
country's level of investment as the average cumulative CAPEX per capita over the country's operators that won a license the auctions in that quarter.[36]

79. The choice of time horizon must balance opposing desiderata. On one hand, a short horizon may fail to capture the relevant investment dynamics. On the other hand, a longer horizon is more likely to capture investment decisions that are unrelated to the auction in question. We thus considered several possible time horizons, namely from 1 to 5 years following the auction. Here, we present results for the midpoint, i.e., the 3-years horizon, but the results with different horizons are qualitatively similar.

80. We also keep the composition of the sample constant across horizons: some quarter-countries may have information for the CAPEX per capita only until 3 years after the auction. Such observations could be included in the 3-years horizon sample, but not in the 4-years one, for example. Therefore, changing the horizon could change the results due to a change in the sample composition, instead of the horizon effect we are trying to capture. To avoid this concern, we have kept the sample composition constant, i.e., the quarter-country combinations presented here have information for all time horizons.

81. Figure 1 shows the raw data for the 3-years horizon, along with a univariate regression line and its prediction interval. The regression line indicates that investment is virtually uncorrelated with average license duration.

Figure 1: Cross-country correlation between license duration and investment



Source: CRA analysis

82. The result appears to be quite sensitive to some extreme data points. For example, removing the observation for Australia in Q2/2011 (with an average license duration of 4

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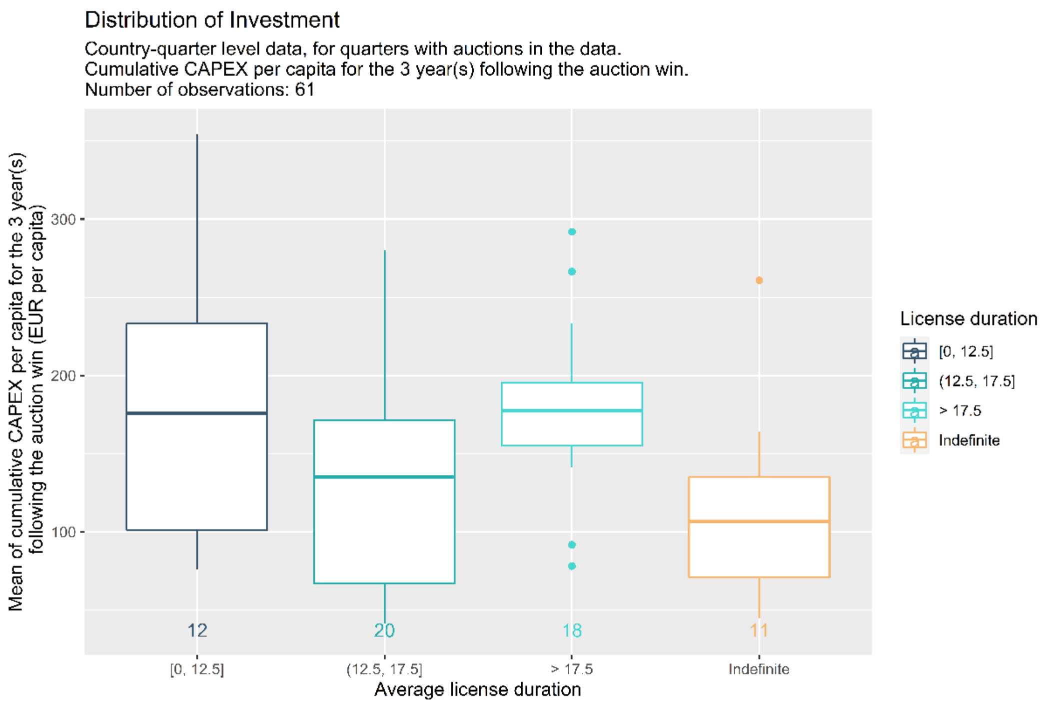
36 Note that if the same operator wins multiple auctions in the same quarter, they are counted multiple times in this calculation. An operator that wins more auctions is presumably more important, so we want our investment measure to reflect that.

years and an average cumulative CAPEX of EUR 353 over 3 years) would lead to an estimate of a positive effect of about EUR 3.3 additional CAPEX (corresponding to 2.1% of average cumulative CAPEX in the sample) per additional year of average license duration.

83. A more serious issue with this regression analysis is that it omits many countries for which there is no definite measure of license duration. A few countries, such as the UK, issue licenses with an indefinite duration, as their renewal is guaranteed.[37] The license duration in these cases do not have a numerical interpretation, so they cannot be included in the analysis above.

84. To circumvent this, we partitioned the sample into 4 bins, depending on their average license duration: from 0 to 12.5 years, between 12.5 to 17.5 years, more than 17.5 years, and indefinite. Figure 2 shows the investment distributions for each of these bins, again for the mean cumulative CAPEX per subscriber in the 3 years following the auction. We also report the number of observations, i.e., quarter-country combinations, for each group.

Figure 2: Distribution of investment per subscription, by license duration type



Source: CRA analysis

85. If we interpret indefinite licenses as the "longest", the data is suggestive of a negative relationship between duration and investment, as the countries with indefinite licenses have the lowest average investment per capita[38]. However, this is not an obvious linear

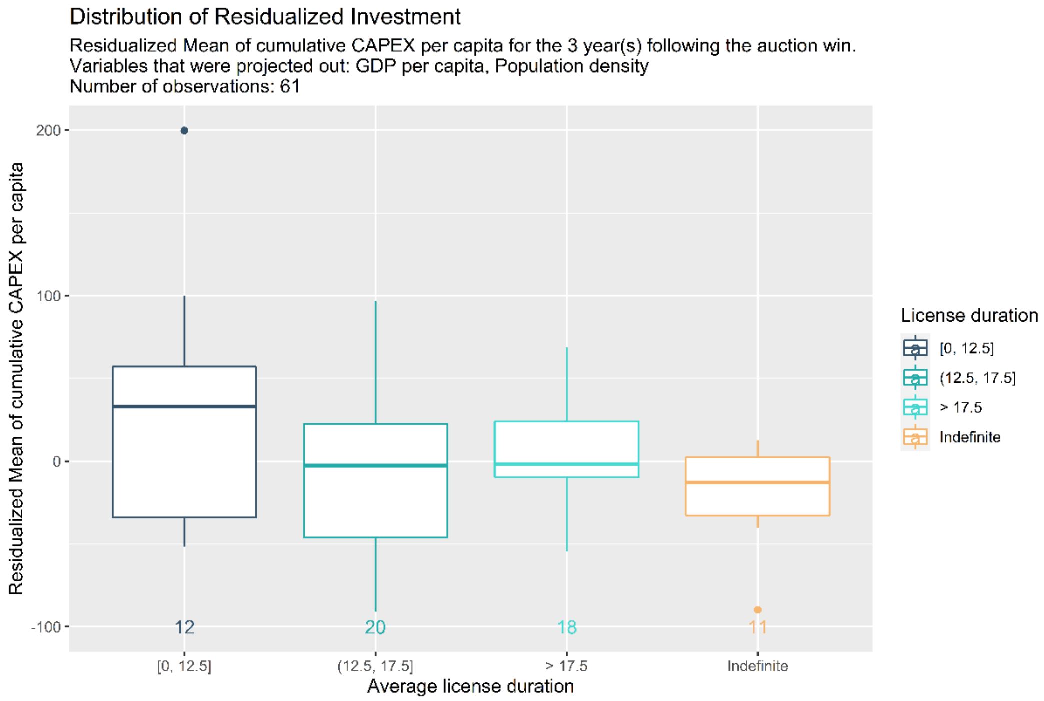
37 After the initial period of the license, the holder is charged annual license fees which, in principle, could induce the holder to return the licence to licencing authorities (we are not aware of this ever happening) or sell it to someone else (a rare occurrence, as the secondary market in spectrum has registered relatively few transactions). License fees thus seem to have had an almost exclusively financial impact and, like the auction prices paid for the original license awards, are not considered in the analyses reported here.

38 They include Czechia, Estonia, Latvia, Spain, UK, and USA. In the robustness appendix, we include regression results which exclude Latvia and the USA from the sample, which yield similar results. The code that was shared with Ofcom can be easily adapted to different scenarios if necessary.

relationship, as the countries with average license duration of at least 17.5 years (but finite) have higher investment on average than those with duration between 12.5 and 17.5.

86. As a robustness check, we have repeated this exercise, but instead of using the mean cumulative CAPEX per subscriber directly, we first regressed it on the quarter-country's GDP per capita and population density and plotted the distribution of the residuals of this regression instead. The regression residuals can be interpreted as the part of investment that cannot be explained by the regressors, i.e., GDP per capita and population density. Figure 3 shows that once we account for the effect of income and population density, investment seems to be negatively correlated with license duration. In particular, the quarter-countries with the shortest durations have the largest level of investment.

Figure 3: Distribution of residualised investment per subscription, by license duration type



Source: CRA analysis

87. We formally test this hypothesis using a regression of investment on a categorical variable for the license duration. We set the [0, 12.5] years of average duration range as the baseline group, meaning that all other groups are compared relative to them. We report the results in Table 12 in which each column represents a different time horizon for the cumulative investment post auction.

88. First, we note that GDP per capita is correlated with investment the way we expected: on average, richer countries invest more. More importantly, the regression confirms the visual inspection above. Controlling for the influence of GDP per capita and population density, we find that all license duration groups tend to invest less than the [0, 12.5] one, although this difference is not statistically significant for the > 17.5 years group, and if we look only at the first year following the auction. Moreover, the indefinite licenses are the ones associated with the least investment.

Table 12: Difference in mean cumulative CAPEX per capita

	Dependent variable:				
	Mean cumulative CAPEX per capita over different horizons				
	1 year(s)	2 year(s)	3 year(s)	4 year(s)	5 year(s)
	(1)	(2)	(3)	(4)	(5)
(12.5, 17.5]	−15.581	−24.090*	−41.050**	−51.787**	−60.765**
	(11.146)	(13.228)	(18.198)	(23.706)	(29.242)
> 17.5	−14.604	−15.538	−27.387	−30.621	−36.003
	(11.859)	(14.074)	(19.362)	(25.222)	(31.113)
Indefinite	−20.278	−31.446**	−52.246**	−70.073**	−86.044**
	(13.042)	(15.479)	(21.293)	(27.739)	(34.217)
GDP per capita	0.002***	0.004***	0.005***	0.007***	0.008***
	(0.0004)	(0.0005)	(0.001)	(0.001)	(0.001)
Population density	0.009	−0.010	−0.030	−0.042	−0.075
	(0.031)	(0.037)	(0.051)	(0.066)	(0.082)
Baseline - [0, 12.5]	13.587	15.279	35.740	46.288	56.010
	(16.447)	(19.521)	(26.854)	(34.982)	(43.153)
Observations	61	61	61	61	61
R^2	0.311	0.555	0.576	0.589	0.598

Note: *p<0.1; **p<0.05; ***p<0.01
Standard error in parentheses.

Source: CRA Analysis.

4.3. An impulse-response analysis

89. When an operator wins a spectrum license it can build or expand its networks that make use of that spectrum. Moreover, some uncertainty on its ability to operate is resolved, which may then also spur investment in their network. We use a regression analysis to assess the hypothesis that investment increases in the initial period following an auction win and whether this effect depends on the duration of the spectrum license that was awarded. This differs from the cross-country analysis in two main ways: first, the level of observation is the operator, not the country. This is important because, as mentioned above, the operator is the agent making investment decisions. Second, we explicitly model the quarter-by-quarter investment dynamics following the auction, unlike the single, cumulative measure we used in the cross-country analysis above.

90. The ability to investigate richer and more detailed investment dynamics comes at a cost though. This analysis is much more demanding in term of data and, as shown below, this results in rather noisy estimates of the relations of interest, thus limiting our ability to learn from the exercise. Part of the problem, which affects also the analyses presented in the later section of this report, is that a large part of the variation in license durations is across countries, not within them, so it is hard to disentangle the effects of different license durations from country heterogeneity deriving from other factors.

91. For each instance in which an operator wins an auction, we collect its CAPEX information between the 4 quarters preceding and the 8 quarters following the auction. We restrict

attention to the operators for whom we have complete CAPEX data.[39] The sample has 3,432 observations, covering 264 different operator-auction combinations, won by 91 unique operators.

92. Capital expenditure requirements may vary considerably not just across countries and time, but also across operators. To control for this, we adopt a dynamic Difference-in-Differences approach and consider an operator's CAPEX index defined by dividing the operator's CAPEX in each quarter by its CAPEX in the fourth quarter before the auction was won. Therefore, for every auction-operator combination, the CAPEX index 4 quarters before the auction is always 100%, and the following quarters can be interpreted as deviations relative to this baseline. This approach is useful because it uses the operator itself as a benchmark for the level of CAPEX. Moreover, with this approach we do not need to normalize the CAPEX level by the number of expected clients (i.e., the per capita or per subscriber measures discussed in section 4.1), so the results here provide a complementary view.

93. The choice of the fourth quarter before the auction as a baseline is of course somewhat arbitrary, but it is motivated by the need to balance two opposing forces. On one hand, taking an earlier date as baseline may cast doubt on the notion that the baseline is a good proxy of the operators' counterfactual (i.e., "but for" the auction) investment levels in the periods after the auction. On the other hand, operators may start adjusting their investment plans well before the conclusion of the auction if they have reason to believe that they will in fact win licences in that auction. We have no information on the time (if ever) when these potential anticipatory adjustments begin – and in fact we cannot exclude that they begin even more than four quarters before the auction, as spectrum auctions are often announced that much earlier – but it is clear that the risk of "corrupting" the baseline investment is higher when the baseline is chosen closer to the auction. We believe our choice of baseline is a reasonable compromise which allows the analysis to provide a useful summary of the dynamics of the investment decisions around an auction.

94. We implement the analysis with the following regression model:

$$CAPEX\ INDEX_{i,t} = \sum_{\delta=-4}^{\delta=8} \beta_{\delta}^{D} f^{\delta}(i,t) \times D(i,t) + controls + \alpha_i + \alpha_t + \varepsilon_{i,t}$$

where we regress the CAPEX index of operator i, at quarter t, on the interaction of the duration of the contract they won, $D(i,t)$ and whether the time interval (in quarters) relative to the auction win is equal to δ, which is given by the function $f^{\delta}(i,t)$. These interactions are associated with the coefficients of interest β_{δ}^{D}. We also include as controls the country of operation's GDP per capita, population density, as well as operator and quarter fixed effects. These fixed effects are important to account for some heterogeneity: for example, the quarter fixed effect can capture the effect of a global downturn in time t that affects every operator. The standard error is clustered at the operator level.

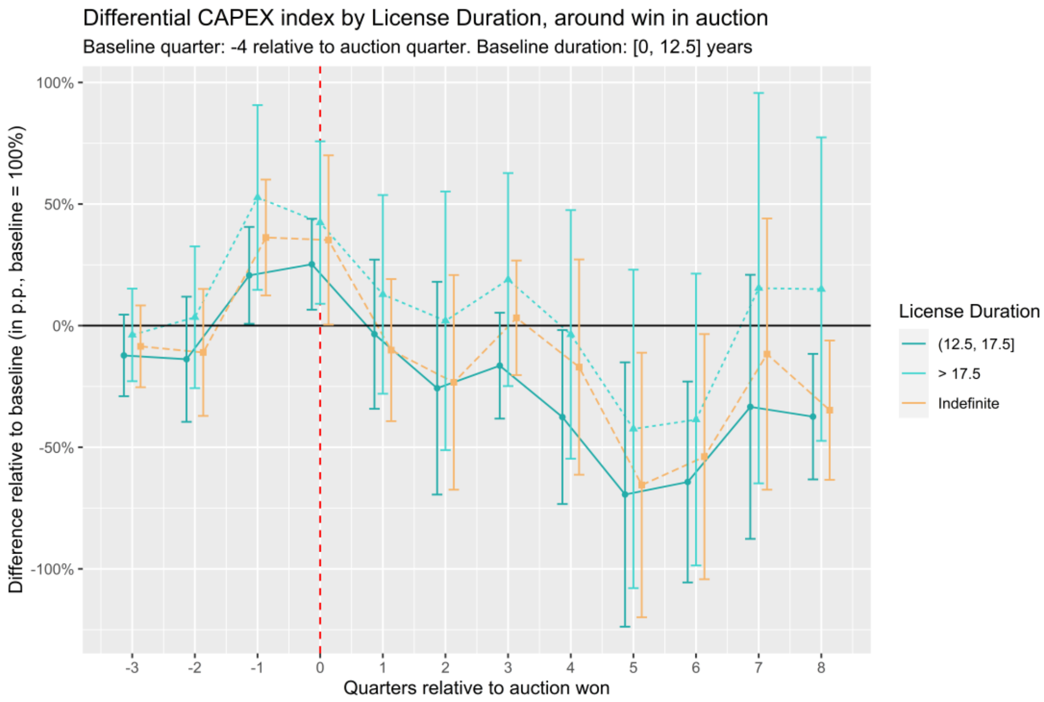
95. To incorporate the indefinite spectrum durations in the analysis, which have no numerical interpretation, the duration variable $D(i,t)$ is categorical, dividing the duration by their years

39 The window of CAPEX data we use is an arbitrary choice but informed by the data. Collecting the data 4 quarters before the auction allows us to create our CAPEX index normalization (explained below in the text) using the same quarter (i.e., Q1, Q2, Q3 or Q4) as the auction. Therefore, the CAPEX index in the quarter of the auction does not reflect any yearly seasonality in investment. The 8 quarters following the auction are a compromise between a long window that allows us to study a longer investment horizon, and the data limitation of not having CAPEX information for a very long period.

into four different bins: [0, 12.5], (12.5, 17.5], > 17.5, and Indefinite.[40] The baseline duration group is [0, 12.5]. The baseline value for the time relative to the auction at -4, so that $\beta^D_{-4} = 0$ for all D by definition.

96. In Figure 4 we plot the β^D_δ coefficients for the non-baseline groups, which can be interpreted as the average percentage point difference in the CAPEX index of those that won a spectrum with duration D, δ quarters away from the auction, relative to the baseline duration $D = [0{,}12.5]$ in that period. For example, a coefficient of 5% means that the CAPEX index is 5 p.p. higher in that period, relative to the baseline group. Due to a limited number of observations, the estimates are not very precise, especially for the > 17.5 group – the confidence interval for some of its coefficients includes both -50% and +50%, for example. Still, the estimates suggest that, if anything, the capital expenditure for groups with "longer" license duration is *lower* than the capital expenditure for the baseline group with short license duration, at least for the initial period of roughly 2 years after the auction is won.

Figure 4: Differential CAPEX index by license duration, around win in auction

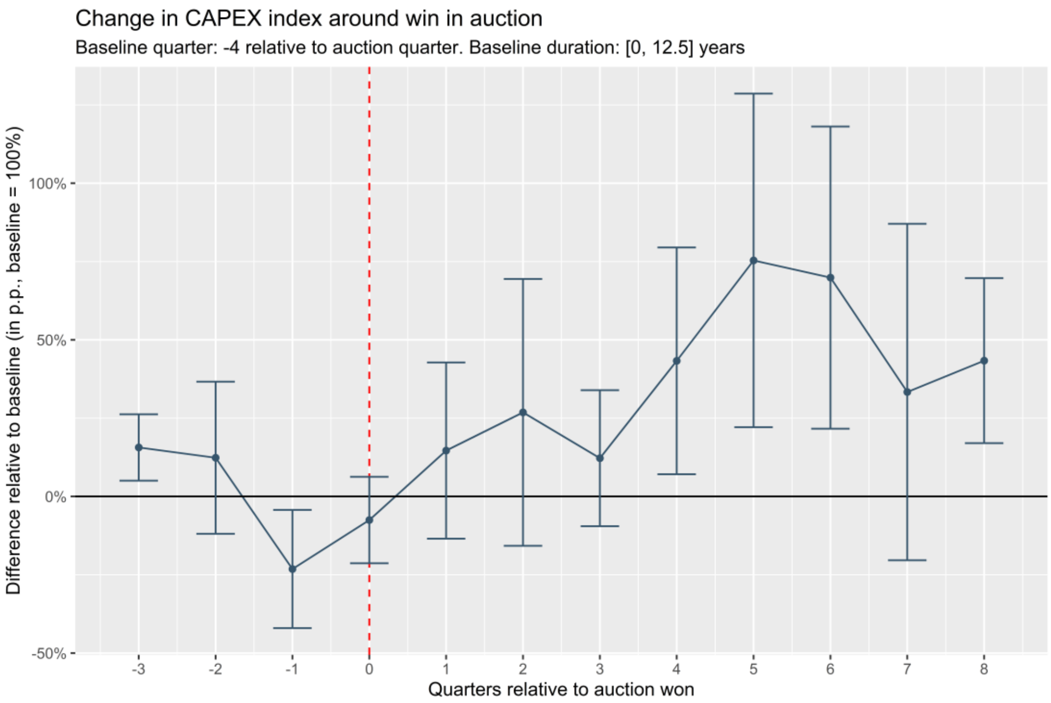


Source: CRA analysis

97. However, this does not mean that investment for these groups decrease following the winning auction. These results are comparisons to the baseline group, i.e., to the operators who won auctions with license duration of up to 12.5 years. But this baseline group itself increases its investment following the auction win, as shown in Figure 5: Change in CAPEX index around auction for [0, 12.5] duration group below.

40 While the definition of the group with indefinite licenses is the same, the code provided to Ofcom can easily be adapted to change this composition if necessary.

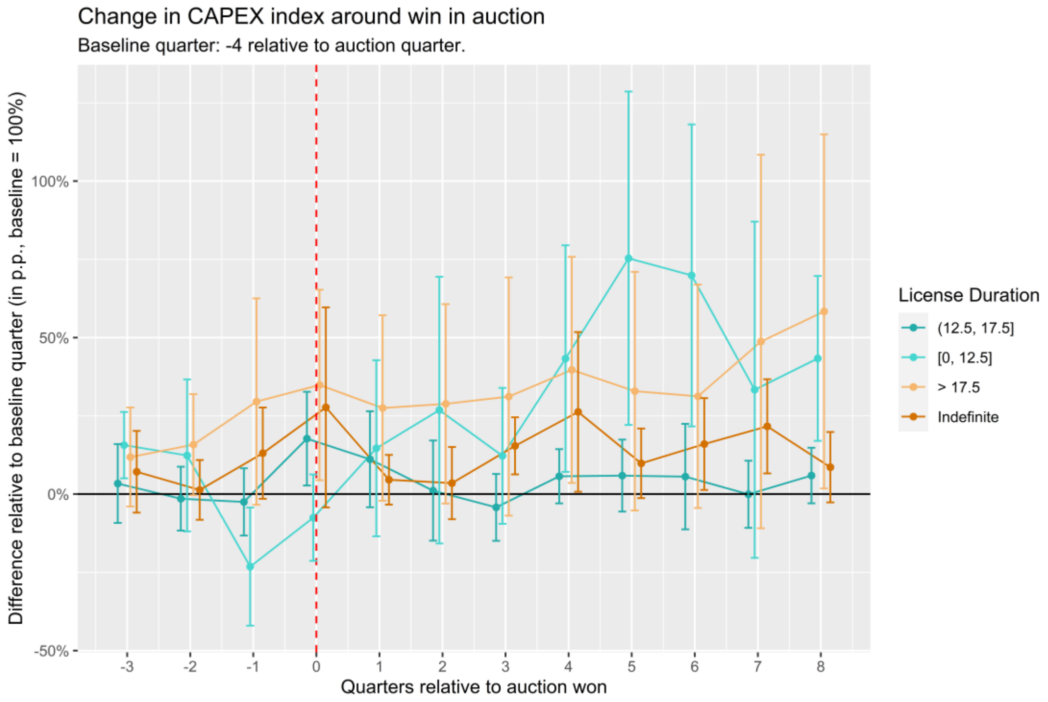
Figure 5: Change in CAPEX index around auction for [0, 12.5] duration group



Source: CRA analysis

98. In Figure 6 we show the investment level estimates for all license duration groups. While the group with the shortest duration increases its investment more than the others, which was already shown in Figure 4, the other groups also increase their investment slightly. The exception is the [12.5, 17.5] years of duration group, whose investment shows no temporal trend following the win in the auction.

Figure 6: Change in CAPEX index around auction for all duration groups



Source: CRA analysis

99. While the data does not allow for precise estimations, we find some evidence that investment is higher when the license issued has a shorter duration. Unlike the cross-country analysis, this evidence is based on operator specific comparison: we track the evolution of their investment over a period in which they win a new spectrum license. Yet, both methodologies reach a similar conclusion: neither of them provides any support to the hypothesis that longer license durations are associated with higher investment levels – if anything, the opposite result finds more support in the data, though not enough to be considered statistically significant or robust.

4.4. An analysis of investments near the end of a license

100. We have so far restricted attention to the period (1 to 5 years) immediately after an auction, so there is still the possibility that license durations may have a stronger impact on the investments in later parts of the investment cycle. For example, the winners of a spectrum auction may invest in the more profitable areas of their country right away regardless of the duration of the license – after all, if they bid for some spectrum rights they should have planned to use them somewhere – but postpone expansions of their networks to less profitable areas (e.g., for lack of financing or managerial resources); the latter may be abandoned altogether if the remaining time on the license is too short. Since we do not have investment data disaggregated at sub-national level, we cannot test this specific theory directly. However, we can investigate whether operators' investments are indeed lower when closer to the expiration of the licence.

101. We focus on the investment made in the later years of a license duration, between the end of the 11th and 15th years of a license.[41] We chose this window because licenses[42] are often issued with a 15 or 20-year duration; for the former, the period between the end of the 11th and 15th years is also the end of its duration, while for the latter there are still 5 years of license remaining. We use this contrast to assess whether the extra remaining years incentivize more investment. We also include in our sample licenses with indefinite duration but remove auctions without information on the license duration.[43]

102. Our CAPEX data has coverage starting in the first quarter of 2011, so the licenses we can study were auctioned as early as in the last quarter of 2000 (so that our data can cover the CAPEX after the end of the 10th year). This coincides with the start of the 3G auctions, therefore we restrict our sample to auctions of this technology, as it removes any heterogeneity that different technical specifications may bring.[44]

103. We defined "investment" as the cumulative CAPEX per capita between the end of the 11th and 15th year of a specific 3G license. That is, for each quarter in this window, we calculate the CAPEX per capita (CAPEX divided by the Country's population times the operator's market share, just like JLL), and then sum across time. Figure 7 shows the distribution of investment for each license duration type we define. Once again, we find that the shortest licenses have the higher investment, although this time the shortest durations are 15, rather 10 years long.

104. There are however some major limitations in this type of analysis. We are trying to ascertain the effect of an event (the MNOs winning a 3G license) on something happening a long time afterwards (their investments 11-15 years later). In the intervening decade many other factors may have affected the MNOs and influenced their investment incentives. In particular, the development of new technologies such as 4G and 5G and the availability of additional spectrum may induce the MNOs to make additional investments, possibly in total or partial substitution to those related to the 3G license under consideration. While this problem is intrinsic in any study covering a long-time horizon, it is compounded by the limitations in the available data. The CAPEX data refers to total capital expenditure for an operator at a certain point in time, but it does not allow us to ascertain that this investment is made specifically on their 3G network. The difficulty of associating investments to specific spectrum licenses also arises for the other analyses in this report, but here it is more problematic both because we are using a longer time horizon – and one in which many MNOs did in fact enter major new technological cycles (4G and 5G) . Therefore, the investment figures may reflect the investment in these other technologies instead, bearing

41 While the original idea was to use the window between the end of the 10th and 15th years, doing so would significantly reduce the number of observations available, as many auctions happened in 2000, and our CAPEX data starts in 2011. See more details below.

42 As discussed below, we had to focus on 3G licenses here, due to limitations in the CAPEX data.

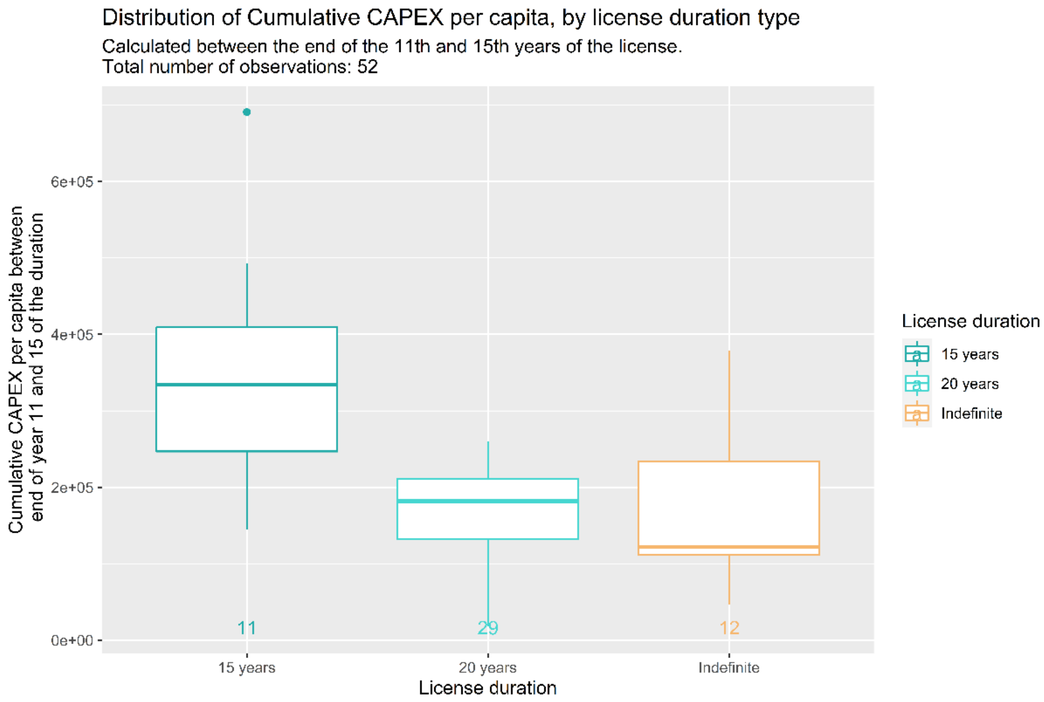
43 There are 6 licenses with 16-years, 1 license with 13-years, and 1 license with 14-years duration which we combine with the 10 licenses issued with 15-years duration. There are 3 licenses with 19-years duration, which we combine with the 30 licenses issued with 20-years duration. We also have 13 licenses with indefinite durations.

44 We only have 40 operator-3G auction combinations that have complete CAPEX records for the period between the end of the 10th and 15th years of the license. However, there are another 11 auctions that happened in 2000, so they have missing CAPEX information only for the 11th year. Therefore, we report results using the window between the end of the 11th and 15th years instead, increasing our number of observations by 27.5%, to 51.

little resemblance to the incentives posed by the 3G license – and hence the license duration that is used here.

105. We try to address this with the same "residualisation" strategy employed in the cross-section analysis. Using our auction data, we can determine whether each operator had additional 4G or 5G licenses during the period we analyse.[45] Therefore, we first regress our investment measure in indicator variables for ownership of 4G and 5G licenses, along with GDP per capita and population density (both measured at the end of the 15th year of the 3G license). In Figure 8, we plot the distribution of the residuals of this regression, by the type of license duration. Qualitatively, there are no changes in the investment patterns even after removing the effects of having licenses for newer technologies, GDP per capita and population density.

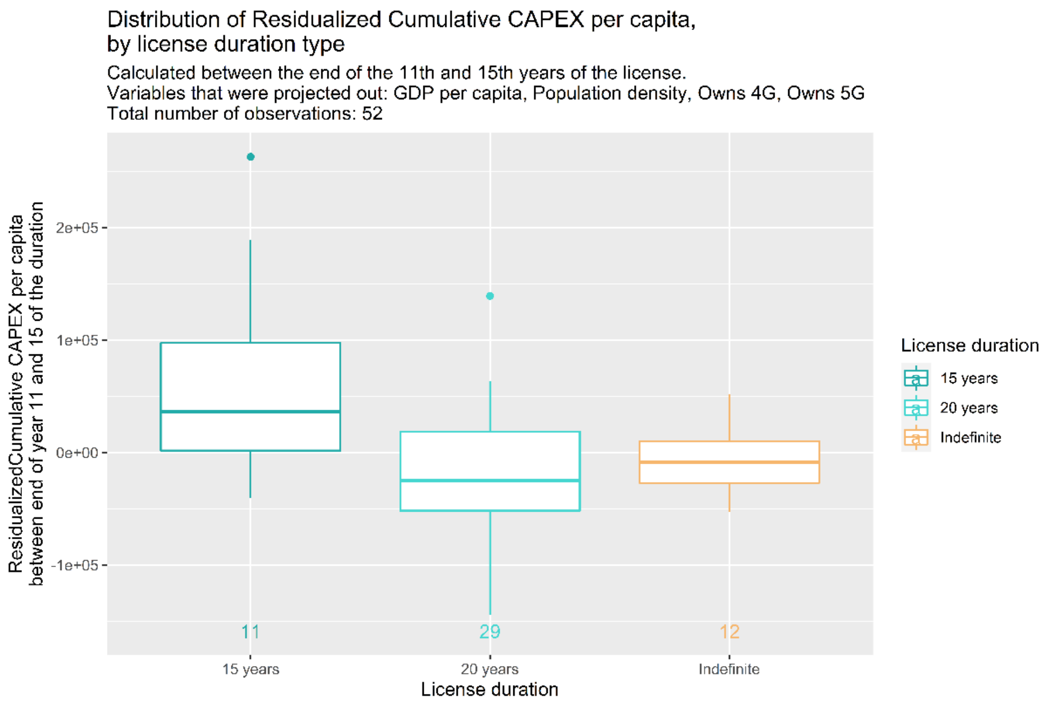
Figure 7: Distribution of cumulative CAPEX per capita, by license duration type



Source: CRA analysis

45 Specifically, we determine whether they had such licenses 12.5 years after the win in the 3G auction.

Figure 8: Distribution of residualized cumulative CAPEX per subscription, by license duration type



Source: CRA analysis

106. Indeed, we find that the difference in investment between the 15-years duration group and the others is statistically significant, as shown in Table 13. This is consistent with our previous results that found lower investment amongst holders of indefinite licenses. This pattern seems to hold in the latter periods of the license as well.

Table 13: Cumulative CAPEX per capita at later stages of 3G licenses

	Dependent variable:			
	Invesment until end of 15th year from			
	11th year	12th year	13th year	14th year
	(1)	(2)	(3)	(4)
20-years duration	−53.058**	−36.374**	−23.992**	−6.443
	(21.964)	(16.002)	(11.292)	(5.978)
Indefinite	−52.986**	−33.271*	−24.935*	−4.930
	(26.233)	(19.112)	(13.487)	(7.140)
GDP per capita	0.007***	0.005***	0.003***	0.002***
	(0.001)	(0.001)	(0.0005)	(0.0003)
Population density	−149.645**	−98.910**	−60.108*	−27.310*
	(59.184)	(43.119)	(30.429)	(16.109)
Has 4G license	17.988	13.393	12.937	6.795
	(18.520)	(13.493)	(9.522)	(5.041)
Has 5G license	−64.781	−55.436	−34.113	−18.877
	(59.398)	(43.275)	(30.539)	(16.167)
Baseline - 15-years	−62.590	−44.901	−30.965	−26.389*
	(48.431)	(35.285)	(24.901)	(13.182)
Observations	52	52	52	52
R^2	0.677	0.664	0.635	0.601
Note:	*p<0.1; **p<0.05; ***p<0.01			
	Standard error in parentheses.			

Source: CRA analysis.

4.5. License duration and download speed

107. While the main focus of this report is on the relation between license duration and investment, one should not lose sight of the fact that the promotion of investments is only an instrumental policy goal and, as reflected in OFCOM's mandate, the ultimate policy goal is, in economic terms, the promotion of consumer welfare. Investments merely contribute to this goal by allowing operators to offer higher quality service, namely broader coverage, higher transmission speed, lower latency, etc.

108. In this section we begin by investigating whether our data show a positive effect of investment on one specific measure of service quality, namely the speed at which average download speed increased in the transition from 3G to 4G networks. In fact, we find such an effect, even though only at levels that are not statistically significant. Given the lack of evidence of a positive relationship between license duration and investments from our previous analyses, we cannot infer that longer license durations are associated to higher

download speeds.[46] We then investigate whether this measure is correlated directly with license duration, regardless of our measures of investment levels – though we note an important limitation of this approach: in the absence of a clear positive relation between license duration and investment, there is no clear mechanism that can link license duration and download speeds, thus increasing the risk that any relation found here between the two may be spurious or a mere statistical fluke. However, it is also possible to reverse this reasoning: if we found a strong relation between license duration and download speeds that would be a strong indication of a strong link between license duration and investment precisely because there is no other obvious mediating variable between the two – and a strong indication that the failure to detect this link in the previous analyses was due to faults in those analyses or in the underlying data (e.g., total operator CAPEX being too noisy a measure of actual spectrum related investments).

109. Our focus on the 3G-to-4G transition comes at the cost of a substantial reduction in the sample size for our analysis, but is motivated by the need to minimize extraneous influences on the variables of interest.

110. First, our download speed data comes from real consumers that use an online service to test the speed of their internet connection. While this has the advantage of reflecting real usage experience,[47] it poses an empirical challenge: there may be significant time differences between investment in the network and the actual consumption of the service. For example, consumers may need to update their devices before enjoying the latest technology, even if the operator has already done most of the necessary infrastructure investment.

111. Second, download speeds depend not only on the operators' investment in a given period, but also by the operators' much earlier investments, at least within the same technological cycle. In fact, download speeds have been increasing steadily, possibly for a combination of the cumulative effect of operators' investments and because of technological improvements not embodied in investment goods, so the analysis must differentiate between the effect of investment and this temporal trend

112. How easy it is for download speeds to increase also depends on the technological cycle. If a new technology has just been introduced, there are potentially many consumers eager to update, so download speeds may increase quickly. For a more mature technology, the gains in average download speed may come mostly from the gradual (and slower) improvement in infrastructure. For example, when 4G is introduced, average download speed may increase quickly because the more technologically demanding consumers will quickly adopt it and the technical gains of moving from 3G to 4G are large. However, after a few years most of the consumers that want quicker mobile internet connections already

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46 Such inference would not be fully justified even if we had found evidence of a robust positive relationship between license duration and investment. For example, it is theoretically possible that longer licence durations stimulate investments in broader coverage without affecting download speeds, but the CAPEX measure also includes other investments targeted at improving download speed.

47 Another advantage is that the average download speed we use incorporates consumers' take-up of the mobile services. That is, rather than just measuring how quick download speeds can theoretically be, real-world average download speed depends on consumers actually signing up for these quicker services. In turn, the decision to subscribe to these mobile services is partly driven by their prices, which is a quality dimension we cannot explicitly evaluate. Therefore, our results are also indicative of the impact of investment on prices, as lower prices lead to higher demand and average download speeds.

have 4G services, and technical improvements within 4G are less dramatic, so the rise in average download speeds slows down.

113. By focusing on the transition from 3G to 4G we can hold the technological cycle constant, while also having coverage in our data (between 2011 and 2021). We identify the transition from 3G to 4G by the earliest 4G auction an operator wins, along with a restriction that the fastest operator available in that country in the quarter prior to the auction cannot be higher than 8Mbps.[48]

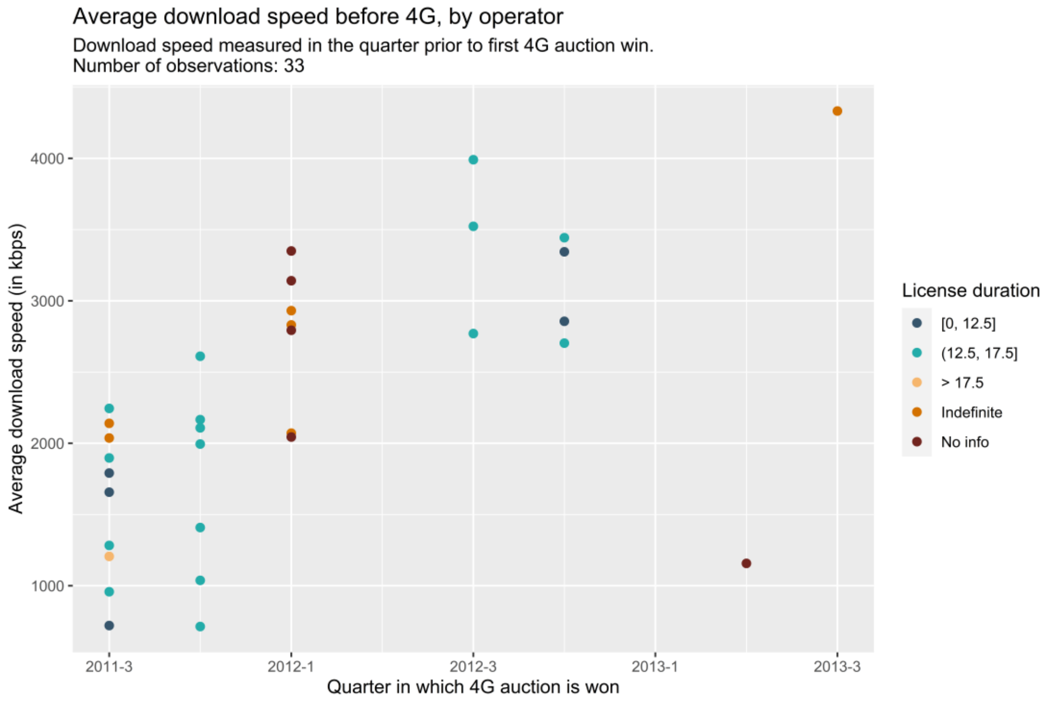
4.5.1. Investment levels and increases in download speed

114. For each operator winning their first 4G auction, we calculate investment as the (log) cumulative CAPEX per capita for 1 to 2 years following the auction, and the time (measured in quarters) it takes for their average download speed to increase by a factor of 2 to 4 (i.e., 100% to 300%), relative to the quarter immediately before the 4G auction. In what follows we report the results for the cumulative CAPEX per capita for 1 year following the auction, but the qualitative patterns are the same regardless of the horizon we consider. To keep the composition of the analysis sample constant, we include in our analysis only the operators with complete records for all horizons analysed here.

115. In Figure 9 we plot the quarter in which the 4G auctions included in our sample are won, along with the average download speed for the corresponding operator in the previous quarter. We can see that most 4G auctions happened in the early 2010s, but also that average download speed increased over time even without a new technology.

48 The frequencies used for 4G may also be used for 5G, so it is not always possible to distinguish between technologies based solely on the frequency being auctioned. However, we know 3G download speeds cannot be higher than 8Mbps (c.f., https://www.tigermobiles.com/faq/mobile-download-speed-guide/), so we also use speed to restrict the sample to transitions away from 3G technology.

Figure 9: Average download speed before 4G auction, by operator



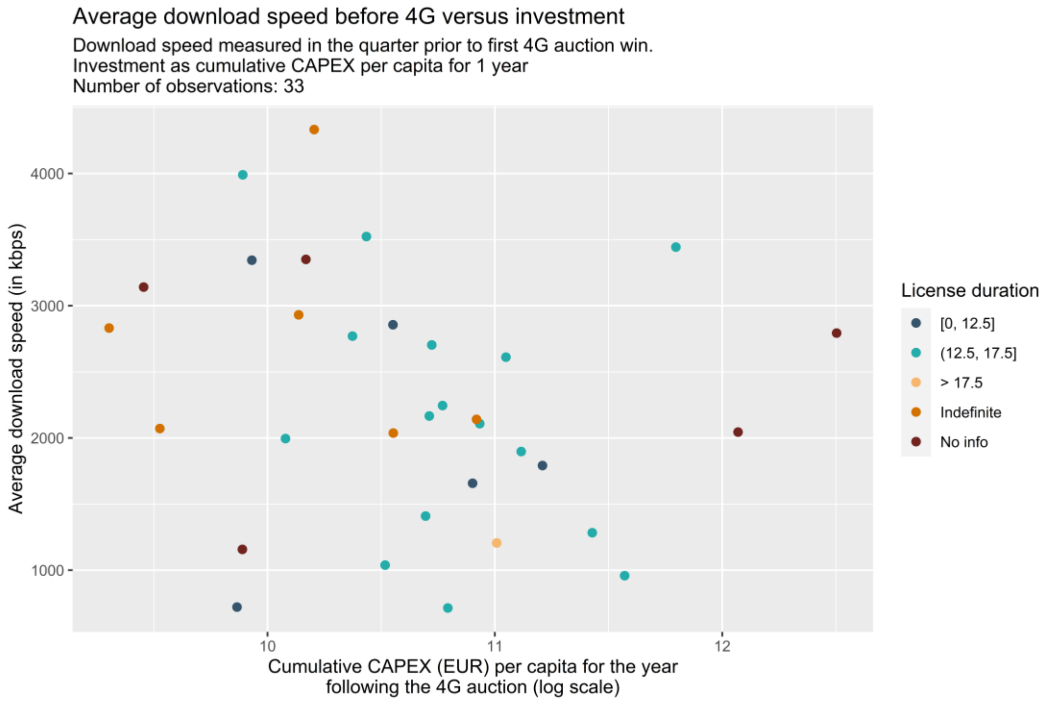
Source: CRA analysis.

116. The average download speed before the auction does not seem to be correlated with future investment, as shown in Figure 10 below. This is reassuring because it ameliorates concerns over reverse causality: if catching up is an inherently "simpler" task *and* operators with worse speeds before the auction invest more in order to catch up, then we would expect the quickest increases in speed to be correlated with the largest investments.[49] But this would not be driven by improvements in speed due to investment; it would be driven by previously slow operators investing more because they needed to catch up. Therefore, knowing that the baseline average download speed is not correlated with subsequent investment is reassuring, because it indicates that our results are unlikely to be driven by these laggard operators. Nevertheless, we include the baseline speed as a control in our regression analysis, as shown below.

117. We further address this issue of reverse causality by using a modified outcome variable: instead of calculating download speed growth relative to the operator's own speed prior to the auction, we use the speed of the fastest operator in the country at the time as the baseline. This way, operators with poor 3G performance will not have an artificially quick evolution simply by catching up to their competitors, as their performance is now compared to the technological frontier. We call this a "absolute" speed growth, in contrast with the "relative" speed growth which uses the operator's own speed as a benchmark.

49 There is an important caveat to this exercise though: we are looking at a period of close to 4 years (from 2011 Q2 to 2015 Q1), in which the technological frontier for mobile operators is sure to have expanded. Therefore, a lower average download speed does not necessarily mean the operator is far from the technological frontier *at the time in which we measure it*. Indeed, the lowest average download speeds are concentrated in the earlier part of the sample.

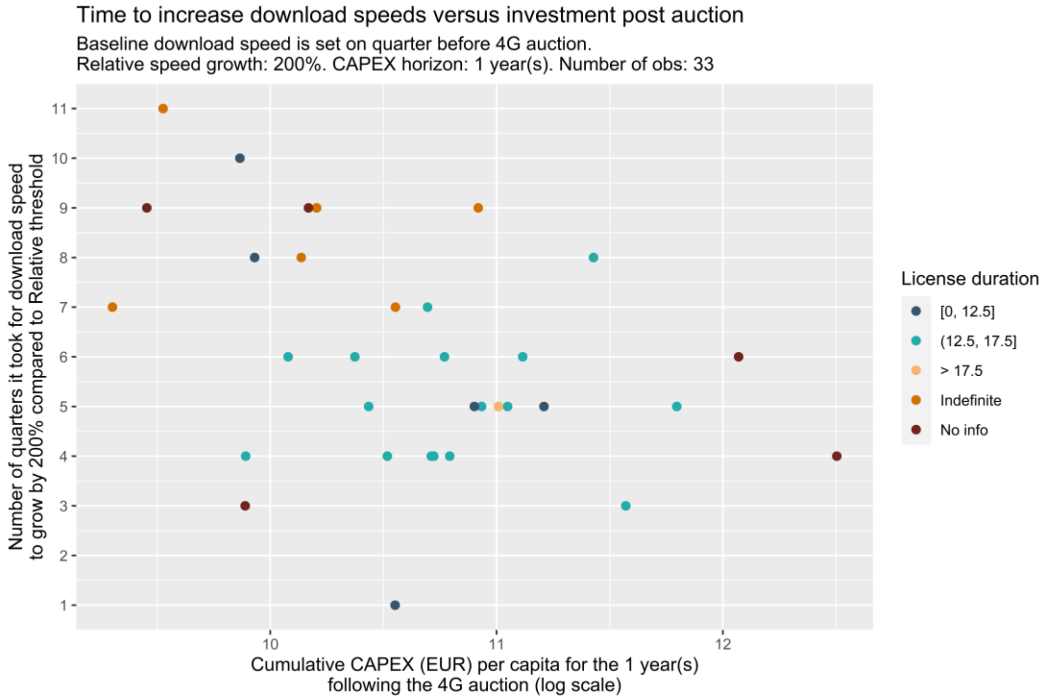
Figure 10: Average download speed before 4G auction versus investment post auction



Source: CRA analysis.

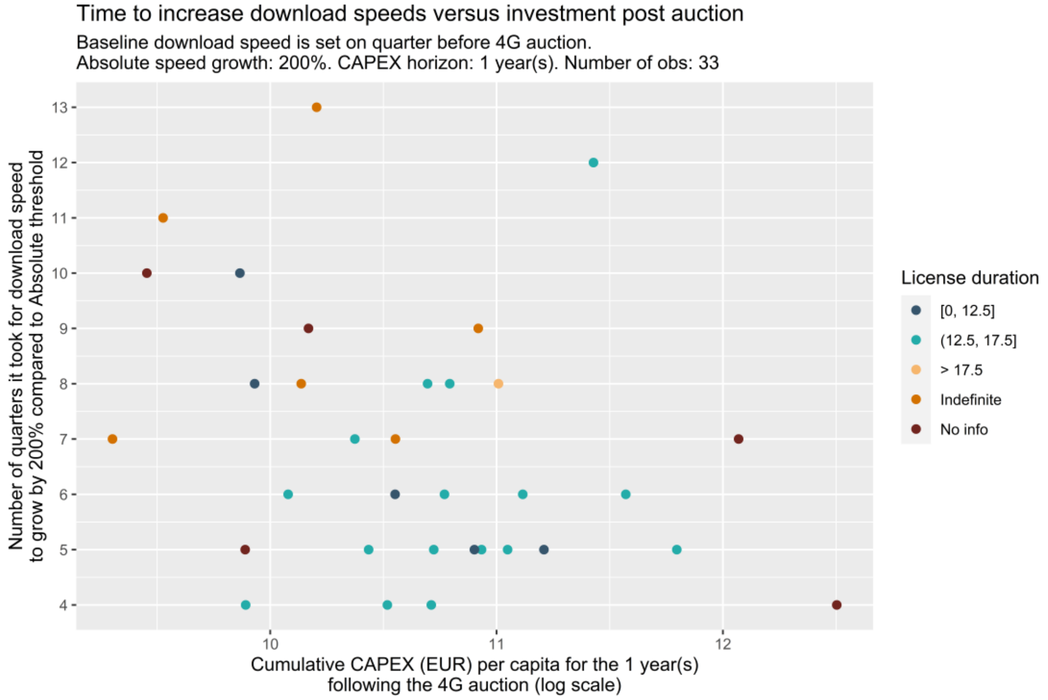
118. Using these average download speeds before the 4G auction as a baseline, we calculate the number of quarters it takes for the operator's average download speed to increase by a factor of 2 to 4, i.e., doubling to quadrupling. In Figure 11, we plot the number of quarters it takes for the download speed to triple versus the cumulative CAPEX per capita in the year following the 4G auction. We can see a negative correlation, as expected: operators that invest more seem to reach this download speed milestone relatively quicker. In Figure 12 we show that this pattern remains true even when we use the fastest operator available in that country-quarter as the benchmark, meaning that this is not purely driven by technological "catch-up".

Figure 11: Quarters to triple average download speed (relative) versus investment post auction



Source: CRA analysis.

Figure 12: Quarters to triple average download speed (absolute) versus investment post auction



Source: CRA analysis.

119. We use a regression model to formally evaluate these relationships, as shown in Table 14 and Table 15, for relative and absolute baselines, respectively. We regress the number of quarters it takes for the average download speed to increase by a certain factor (double, triple, and quadruple in columns (1) to (3), respectively) to the (log) cumulative CAPEX per capita over the year following the 4G auction. We include in the regression model the country's GDP per capita and population density in the quarter of the auction, and the operator's own baseline average download speed itself, for the reasons discussed above.

120. We find that the negative correlation we see in the graphical evidence is not statistically significant once we account for these control variables, in general. Taking column (2) of Table 15 as an example, we find that a 1% increase in cumulative CAPEX per capita over the year following the 4G auction is associated with the tripling of the baseline average download speed happening 0.0148 quarters earlier—and this tripling itself takes, on average, 6.1 quarters. However, the effect of investment is never statistically different from zero at the conventional 5% confidence level, regardless of the growth factor we look at.

121. As shown in Table 15, when we use an absolute benchmark for speed, we find a statistically significant decrease in the time it takes for the download speed to double (i.e., increase by 100%). A 1% increase in cumulative CAPEX per capita over the year following the 4G auction is associated with the doubling of the download speed (relative to the fastest provider) happening 0.2028 quarters earlier.

Table 14: Regression of time required for download speed to increase relative to operator's own speed on cumulative (1-year) CAPEX per capita (log scale)

	Dependent variable:		
	Relative DL speed growth of		
	100%	200%	300%
	(1)	(2)	(3)
Cumulative CAPEX (log scale)	−1.167	−1.480	−0.297
	(0.690)	(0.922)	(1.139)
Baseline download speed	0.0003	0.0001	0.001*
	(0.0003)	(0.0004)	(0.001)
GDP per capita	0.0001	0.00004	−0.00001
	(0.0001)	(0.0001)	(0.0001)
Population density	2.896	−1.617	−2.648
	(2.428)	(3.242)	(4.006)
Dependent variable average	4.13	6.1	7.39
Average investment (EURO per capita)	57251.43	57251.43	57251.43
Observations	31	31	31
R^2	0.181	0.215	0.217
Note:	*p<0.1; **p<0.05; ***p<0.01 Standard error in parentheses		

Source: CRA Analysis.

Table 15: Regression of time required for download speed to increase relative to fastest operator's speed on cumulative (1-year) CAPEX per capita (log scale)

	Dependent variable:		
	Absolute DL speed growth of		
	100%	200%	300%
	(1)	(2)	(3)
Cumulative CAPEX (log scale)	−2.028**	−1.620	−0.996
	(0.854)	(1.109)	(1.185)
Baseline download speed	−0.001**	−0.0003	−0.001
	(0.0004)	(0.001)	(0.001)
GDP per capita	0.0001*	0.0001	0.0001
	(0.0001)	(0.0001)	(0.0001)
Population density	−0.335	−2.540	−9.350**
	(3.005)	(3.902)	(4.166)
Dependent variable average	5.45	6.9	8.87
Average investment (EURO per capita)	57251.43	57251.43	57251.43
Observations	31	31	31
R^2	0.289	0.131	0.200
Note:	*p<0.1; **p<0.05; ***p<0.01		
	Standard error in parentheses		

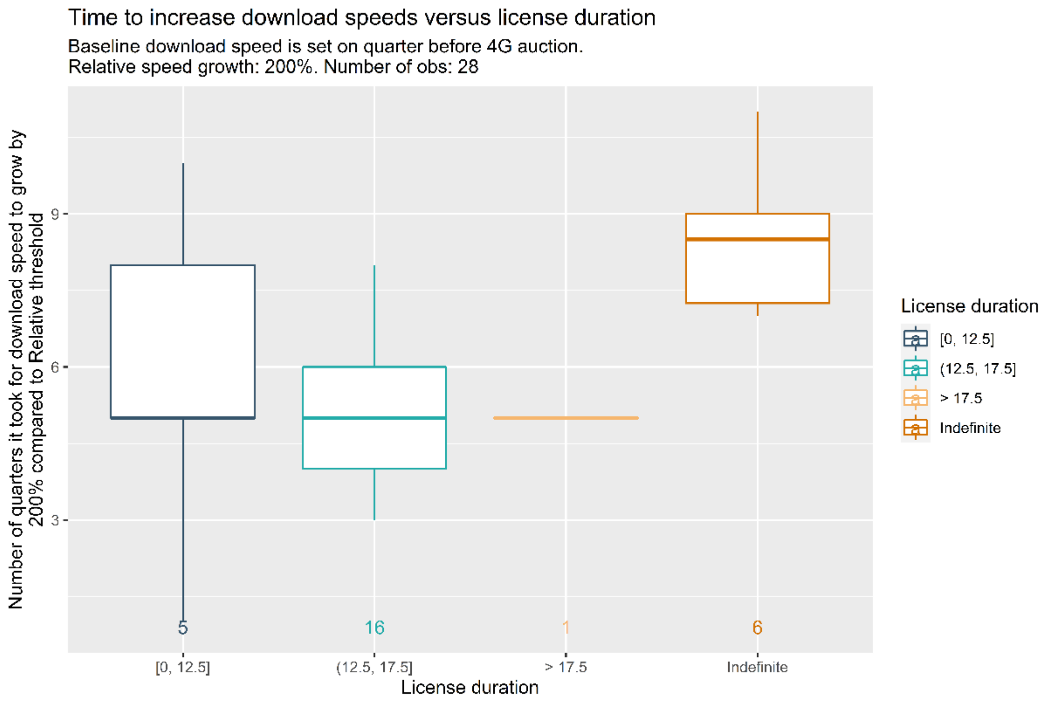
Source: CRA Analysis.

4.5.2. License duration and increases in download speed

122. Finally, we can analyse the direct relationship between license duration and download speeds. The findings above suggest this relationship is unlikely to be strong. We expect license duration to affect download speeds through investment. However, we found little evidence of an impact of license duration on investment, and little evidence of an impact of investment on download speeds.

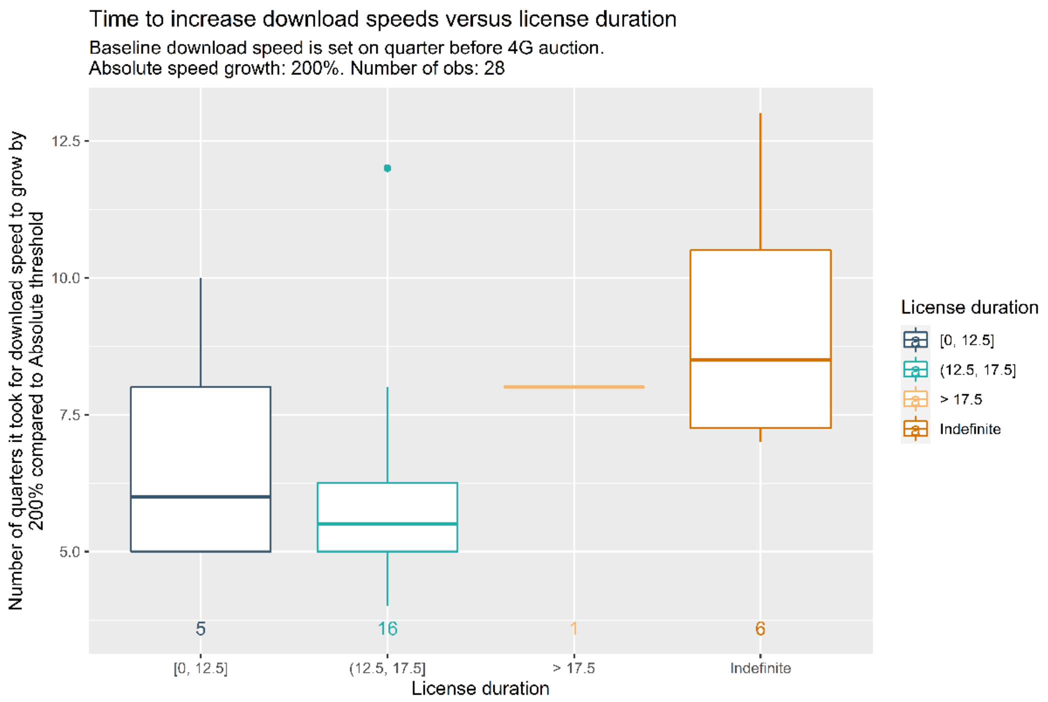
123. In Figure 13 and Figure 14 we plot the distribution of the time it takes for download speeds to triple relative to the relative and absolute baselines, respectively, by license duration. The distributions seem different by contract duration, with the indefinite licenses standing out as the slowest evolution of download speeds. However, it is also clear that our sample is limited in size.

Figure 13: Time to increase relative download speeds versus license duration



Source: CRA analysis.

Figure 14: Time to increase absolute download speeds versus license duration



Source: CRA analysis.

124. We use a regression framework to assess this relationship more rigorously. It allows us to control for some extra covariates, such as the baseline download speed, GDP per capita and population density, and to evaluate if the differences we observe are likely to be due to chance or not.

125. The results for the relative (Table 16) and absolute (Table 17) download speed growth are similar. We cannot statistically distinguish the download speed growth for any groups at the conventional confidence levels. The point estimates have large magnitudes, but they are not precise enough for us to statistically distinguish them from being zero.

126. For example, when looking at the relative download speed growth, the regression indicates that, everything else constant, indefinite licenses take 1.835 quarters longer to quadruple their relative download speed, relative to the baseline group with duration of up to 12.5 years. However, we cannot reject the null hypothesis of no difference between the two groups due to the limited sample size.

Table 16: Regression of time it takes for relative download speed to grow on license duration

	Dependent variable:		
	Relative DL speed growth of		
	100%	200%	300%
	(1)	(2)	(3)
12.5 to 17.5 years of duration	−1.481	−1.836	−1.181
	(1.060)	(1.346)	(1.844)
More than 17.5 years of duration	−0.879	−2.481	−1.227
	(1.721)	(2.185)	(2.994)
Indefinite duration	0.166	1.266	1.835
	(1.220)	(1.549)	(2.122)
Baseline download speed	0.0003	−0.0004	0.0003
	(0.0003)	(0.0004)	(0.001)
GDP per capita	0.0001	−0.00001	−0.00004
	(0.00005)	(0.0001)	(0.0001)
Population density	1.412	−3.636	−2.627
	(2.703)	(3.432)	(4.702)
Baseline duration (up to 12.5 years)	2.489*	8.749***	8.241***
	(1.236)	(1.570)	(2.151)
Dependent variable average	4	6.08	7.23
Observations	26	26	26
R^2	0.365	0.555	0.442
Note:	*p<0.1; **p<0.05; ***p<0.01 Standard error in parentheses		

Source: CRA Analysis.

Table 17: Regression of time it takes for absolute download speed to grow on license duration

	Dependent variable:		
	Absolute DL speed growth of		
	100%	200%	300%
	(1)	(2)	(3)
12.5 to 17.5 years of duration	−0.713	−0.759	0.180
	(1.512)	(1.954)	(2.293)
More than 17.5 years of duration	1.114	0.404	−0.767
	(2.454)	(3.171)	(3.723)
Indefinite duration	1.275	2.622	2.508
	(1.740)	(2.248)	(2.639)
Baseline download speed	−0.001**	−0.001	−0.001*
	(0.0004)	(0.001)	(0.001)
GDP per capita	0.00001	0.00003	0.0001
	(0.0001)	(0.0001)	(0.0001)
Population density	−1.018	−2.495	−8.565
	(3.855)	(4.981)	(5.847)
Baseline duration (up to 12.5 years)	8.151***	8.019***	10.634***
	(1.763)	(2.278)	(2.675)
Dependent variable average	5.54	6.88	8.62
Observations	26	26	26
R^2	0.420	0.350	0.330
Note:	*p<0.1; **p<0.05; ***p<0.01 Standard error in parentheses		

Source: CRA analysis.

5. CONCLUSION

127. The relationship between the duration of spectrum licences and MNO's incentives to invest in the networks that make use of that spectrum is, as a matter of economic theory, a complex, multifaceted one. We have found that, empirically, it is also an elusive one.

128. The previous work in the literature (the JLL paper) in our view can mainly be used to gain some initial insights into the statistical relationships between some of the variables of interest. In this context we also believe that alternative variables that focus on the remaining instead of total license duration better capture the relevant economic relationship of interest between license duration and capital investment. When applying the empirical JLL approach to the (more recent) data available to us, we obtain effects that are smaller in magnitude and are often not statistically significant. This also holds when assessing the robustness using different definitions of per capita CAPEX and license duration.

129. We have developed several other empirical approaches that try to focus more directly on specific parts of the MNOs' network investment cycles, and on the different parts of the licenses' lifetime: a country-level analysis of investments in the five years after a spectrum auction, an operator-level, dynamic "Difference-in-Difference" analysis of investment the year before and in the two years after winning a spectrum auction, a comparison of operators' investments 11 to 15 years after winning a 3G spectrum license between 15-year licences and longer ones, a direct comparison of the increases in download speed in the transition from 3G to 4G networks for different durations of the 4G licenses. None of

these analyses found any evidence of a positive relation between longer license durations and increased investments. If anything, they suggested that licenses with longer (and, especially, indefinite) duration are more likely to be correlated with *worse* investment and network quality outcomes rather than better one – though this was by no means a robust (or even statistically significant) result.

130. We acknowledge that this absence of robust evidence is not evidence of the absence of a relation (or either sign) between license durations and investments or network quality. Instead, it may be due simply to the lack of sufficiently high-quality data to uncover it.

131. Some aspects of this data scarcity are an ineliminable feature of the industry: investments in networks go in pluriannual technological cycles and, by the time one had accumulated data on enough of these cycles it is likely that structural changes in the market and the technology make the evidence from the oldest cycles almost worthless. But our analysis would have definitely benefited from a few more years' worth of data since the ones available to us (for the 2011-2021 period) roughly covered just the 4G investment cycle and the beginning and end of the next (5G) and previous (3G) cycles.

132. Another important limitation of our data is that it only included total operator-level CAPEX, hence aggregated the investments aimed at putting into use all the spectrum rights held by the operator (as well as any other, non-spectrum-related investment). Disentangling the investments in exploiting different spectrum bands may also be intrinsically impossible, e.g., because investment may be largely specific to each network generation (2G, 3G, 4G, etc.), but each network may use several spectrum bands and the same band may be used in several networks.[50] However, it would still be theoretically possible – and very useful – to have a more disaggregated view of MNOs' investment, e.g., by asset type (radio network, core network, other investments), possibly by network generation, or by geographical dimensions (e.g., investments to increase rural coverage versus investments to increase download speeds in urban areas), as this could allow a more precise analysis of the relation between license duration and specific types of investments that may be affected by it.[51] National regulatory authorities may be in a position to acquire such data. However, whether it is realistically feasible to obtain data from a sufficiently large number of countries is a harder question.

133. There are, of course, several other kinds of data – and models – that could shed further light on MNO's investment incentives. For example, MNO's financial situation and access to capital markets may also be important determinant of investments and the corresponding data could allow the construction of more sophisticated models of investment decisions where the duration *and price* of spectrum licenses could be better accounted for.

At the moment, however, we can only proceed on the basis of the data we have and the best summary we can give of them is that they do not provide any reliable evidence that longer spectrum license durations induce operators to invest more in their network or to improve their service quality.

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50 The possibility of re-farming spectrum (e.g., taking spectrum originally dedicated to 3G service and moving it to a 4G network) often further confuses this relation and direct data on how exactly spectrum is used would also be useful.

51 Similarly, it may be useful to have geographically disaggregated data on download speeds or other measure of service quality.