Review of the ACMA expiring spectrum licence pricing (phase two)

Prepared for the ACMA

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Executive Summary

The ACMA has published its updated preliminary views on pricing for renewal of expiring spectrum licences (ESL). In doing so, it has largely adopted DotEcon's recommendations from our peer review of its benchmarking methodology. We find that these recommendations have been implemented logically and accurately.

Selecting a central price estimate

At this stage, the ACMA has added an approach for calculating single price points (rather than price ranges), by selecting either the median or the geometric mean to best align results from the entire sample with those from certain "cohorts" (subsamples of the data based on GDP per capita or population density similarity to Australia). This is a reasonable approach given uncertainties about which estimator is best and whether subsamples should be used to improve comparability with Australia.

However, we think that a simplified approach – ultimately supporting the same conclusions – can be more transparent and better grounded in standard statistical method. Therefore, we break the ACMA's "Step 6" into two separate issues: choosing the best central estimator of prices and considering whether to use a subsample.

Choosing an appropriate central estimator

An appropriate central estimator for prices should, as far as possible, minimise errors, including both under- and over-estimates, and be robust to possible errors of various types in benchmark data.

The ACMA has rightly focussed on medians and geometric means as central estimators rather than the simple arithmetic mean as these are more robust to high price outliers. Therefore, the approaches taken so far are already conservative in nature and give greater weight to avoiding overestimates.

We also want a good central estimate to be statistically efficient, that is to assimilate the available information within the sample data and create an estimate that has low variance. The geometric mean typically outperforms the median in this regard, but is less robust to the impact of outliers. Whilst the median is robust to outliers, it can be sensitive, especially in small samples, to errors in observations close to the median.

This leads us to recommend using the geometric Hodges-Lehmann (GHL) estimator, which is a composite combining the best features of geometric mean and the median. We demonstrate that this central estimator has better performance than either the median or the geometric under reasonable assumptions. This statistic is associated with the Mann-Whitney U-test already used in the 8-step methodology and achieves a good balance between robustness and efficiency. It avoids the need to choose between median or geometric mean using some ancillary criteria.

The resulting final prices using the GHL estimate on the entire sample are very similar to those calculated by the ACMA using its existing Step 6.

Cohorts and use of subsamples for comparability reasons

Under our approach, we consider cohort issues as a separate step, having picked a central estimator purely on statistical and risk management grounds. We test for statistically significant differences in prices between benchmarks inside and outside of the cohort using our preferred estimator, which in this case is equivalent to a standard Mann-Whitney test.

The definitions of these cohorts (in particular, the threshold for population density) currently leave very few observations remaining. This is potentially concerning and implies that sufficient evidence is needed to justify so significantly pruning the available data. Furthermore, we need to consider that observations of individual auction prices are likely correlated (especially when in the same region and occurring at similar times). This means that statistical tests will tend to overstate the evidence found to reject their null hypothesis, with the consequence that we may conclude too readily that a cohort differs significantly from the full sample. A test for a difference at the boundary of statistical significance is, therefore, not adequate evidence for severely restricting the sample being considered. This suggests a conservative approach to cohort testing, which can be achieved by requiring a stricter (1%) confidence level before filtering. This also addresses the problem of running many statistical tests for different restrictions and finding significant effects simply through excessive data mining rather than a cohort being genuinely different.

Grounds for using cohort subsamples

We have broad concerns about the use of population density as a metric for considering the comparability of countries, as it may give a misleading picture. Population density may be lower because of having a large swathe of territory in which terrestrial mobile services will not *ever* be deployed (and which are not subject to coverage obligations). This is a particular concern for the future with the growth of D2D satellite services. We have considered an urbanisation measure as an alternative that avoids this problem.

On the basis of urbanisation, Australia is not exceptional and there is no good case for restriction of the full sample.

In regard to GDP differences, these are already largely controlled through the use of PPP exchange rates and there is no statistically significant evidence that further restriction of the data would be justified.

Using the benchmark sample collected by the ACMA up to this point, we conclude that grounds for restricting the sample to a cohort are weak.

Trends

Considering the fundamental drivers of price trends – cumulative spectrum volume, spectral efficiency, and consumer demand – we would expect periods of downward price movements following technology innovations or significant spectrum release. However, these changes are likely to be overlaid on a more fundamental upward trend caused by growth of bandwidth requirements. Therefore, as a matter of principle, even if there is a historic decline in real spectrum prices, it is unsafe to extrapolate this into a sustained, long-term decline in prices.

Exchange rates

PPP exchange rates remain the most suitable way of adjusting values of long-term spectrum licences. This is a standard approach for benchmarking and is used by other NRAs such as Ofcom.

Including and excluding observations

Observations should only be excluded based on objective characteristics or where there is obvious measurement error. The ACMA should rely on the systematic use of robust statistics that allow for some problematic data being present, rather than subjective exclusion of outliers. We have undertaken jackknife analysis to identify the sensitivity of overall results to individual observations. This supports the view that our proposed statistics are robust.

Stakeholders have suggested further awards to add to the benchmark sample. Not all of these are suitable, often because the award was not competitive, but many of them can be included. The main effect of expanding the sample is that we find a significant difference between countries inside and outside of the GDP cohort for the 3.4-3.8 GHz bands (as above, that difference was not significant based only on the data already published by the ACMA). This is an expected result of expanding the sample as doing so increases statistical power.

Future price adjustments

Renewal dates are still several years off for some bands and the ACMA intends to update prices by reapplying its ESL methodology when new award data and economic statistics become available. The methodology developed in this report is reasonably general and should cope with data revisions and additions. However, even with a clear established methodology, there is no avoiding the fact that automatic updating of prices might not be possible in extenuating circumstances. Therefore, the ACMA should fix price levels well in advance of licence expiry dates to provide certainty to operators. These prices can be fixed in nominal terms and subsequent inflation adjustments mechanistically applied.

1 Introduction

The majority of spectrum licences in Australia expire between 2028 and 2032 and the ACMA is preparing to renew these Expiring Spectrum Licences (ESLs).

The ACMA has recently consulted on Stage 4 of this process, where it published its updated preliminary views on licence prices. The approach taken by the ACMA incorporates previous recommendations made by DotEcon in a peer review of the benchmarking methodology that the ACMA published at Stage 3. Whereas Stage 3 published provisional price ranges, Stage 4 refined this to propose single price points.

ACMA's 8-step process

The ACMA's current ESL valuations are based on an 8-step process:

1. Compilation of benchmark valuation data for spectrum using domestic and international spectrum awards;
2. Conversion of data to standardise licence duration;
3. Conversion of award prices to AUS dollars using PPP exchange rates;
4. Using Australian CPI to rebase awards occurring in different years to the current year;
5. Considering the potential for time trends within the data;
6. Determining a single price point for each set of bands;
7. Using a CPI forecast to carry each single price point forward to the relevant renewal date of licences;
8. Converting for the relevant duration of the renewed licence.

Our role

DotEcon has been asked to provide expert analysis on the application of the ACMA's proposed benchmarking approach and stakeholders' responses to the public consultation on the ESL methodology. The ACMA has highlighted the following aspects of the methodology as areas of particular importance:

- deriving a single price;
- sample selection;
- time trend identification and, if relevant, adjustments; and
- adjustments for payment timing.

This consultation exercise is intended to allow the ACMA to refine its proposed methodology. The intention is, as far as possible, to set out a robust and reasonably general analytical procedure that could be reapplied if the benchmark dataset were extended or revised. This could potentially allow for subsequent revision of estimated prices given new data without methodological changes.

In this report we first discuss methodological issues, in particular how deriving a single price relates to cohort issues, using the ACMA’s existing sample. We then address data selection issues and reapply the methodology to an updated sample incorporating recent awards and other suitable stakeholder suggestions.

2 Estimation of single price points

2.1 General approach

The ACMA has derived a single price per MHz-pop per year for each band group based on central estimates of market value. In Step 6 of its 8-step process, the ACMA:

- calculates two standard statistical measures of central tendency, the median and geometric mean; then
- selects between these statistics by checking against cohort subsamples (in regard of GDP and population density filters),[1] and if necessary, broader policy objectives.

Why a simple arithmetic mean is not used

The mean, the most common statistic used to measure central tendency, has not been used in this analysis because it is much more strongly affected by high price observations than either the median or geometric mean. We observe that spectrum price data is typically positively skewed (i.e. its distribution has a longer upper tail than lower tail). As a result, the mean will be higher than both the median and the geometric mean. Therefore, both the median and the geometric mean are conservative estimates in these circumstances, as discussed in Annex A.

Restricting the data considered

The ACMA's process for deriving single price points involves '*cohorts*' i.e. considering prices in a subset of countries with similar GDP per capita or population density to Australia. This has been used primarily to validate the measure of central tendency on the whole sample by checking that this lies within an interquartile range (IQR) for cohorts and using that IQR as a collar on the estimate if necessary.

If we adopt a permissive approach to allowing data into the benchmark dataset, as has been done here, clearly it becomes necessary to consider the possibility that the dataset is too broad and may contain data points that are less comparable with Australia. Therefore, some restriction of the data to the more comparable cases may be needed, especially if want to set out a reasonably general analytical procedure that can applied without further modification to different possible sets of data.

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[1] Where neither full sample central estimate falls within the cohort IQR, the ACMA selects a cohort quartile instead of the central estimate.

Using the IQR of cohorts is a potential means to achieve this. However, we need to consider the impact of small sample sizes when restricting the sample, as uncertainty about estimates increases rapidly. Conventional statistical testing approaches (i.e. whether a cohort is significantly different from the sample as a whole) have merit as they give a framework that considers all these issues. We discuss how a validation test based on the IQR of a cohort differs from a traditional statistical test in detail in Section 5.

Under- and over-estimation

Given this, we think it is helpful to focus first on the statistical properties of various central estimators, then return to cohort issues in Section 5.

Respondents have rightly raised the point that any central estimator of market price tends to balance the risks of under- and over-estimation in the context that the estimator is being used (i.e. as a licence renewal price). Therefore, we need to consider both:

- the consequences of under- and over-estimation against the ACMA's policy objectives for licence renewal prices; and
- the statistical properties of different estimates.

We consider these points in turn in the following subsections.

2.2 Impact of under- and over-estimation

Reflecting policy objectives

In setting a single price, the ACMA needs to consider the balance of risks for setting prices too high and too low against its policy objectives. One of the main contentions from operators is that these risks are asymmetric, with the consequences of setting prices too high being more severe, which suggests using conservative estimates of market value.

However, in practice there is a wide range of considerations, as we set out below. Risks of under- and over-estimation need to *both* be controlled and a balance struck.

Incentives to use spectrum efficiently

Over-estimation risks

Licensees have understandably focused solely on risks from prices being too high. The most important of these is the risk that, if set too high, ESL prices could lead to licences not being renewed and the spectrum instead being inefficiently left fallow. In practice, operators need to retain spectrum for continuity of services, so this risk is only material in relation to marginal blocks of spectrum and then only if prices were sufficiently high.

Under-estimation risks

There are also risks from prices being set too low, such as weaker incentives for licensees to reorganise their spectrum holdings by returning or transferring spectrum. Ongoing spectrum fees provide an incentive for return of spectrum that is not being used, or being used in a highly inefficient manner, as these costs are avoided.

Secondary market transactions (including sales and leases) can be driven both by:

- opportunity costs (i.e. that spectrum could be transferred to another user prepared to pay more for it than the value the current user derives); and
- actual incurred costs (e.g. ongoing spectrum fees and potentially also costs of meeting obligations on coverage).

Incurred costs of holding spectrum licences may be a more effective incentive to secondary transactions, in that they are directly experienced and observable by the current licensee.[2] In contrast, opportunity costs are hypothetical by nature and occur where an alternative user has higher value, which cannot be known for certain by the current licensee. Given this uncertainty, setting renewal fees at a best estimate of market value should assist the licensee in identifying where there might be opportunities for efficient secondary trades.

Operators will also be incurring ongoing *actual* costs of financing spectrum that might be avoided through a secondary transaction. To the extent that spectrum costs are deferred through ongoing fees there will be direct avoidable costs of holding that spectrum. Notice that secondary trading does not require there to be a more efficient entrant ready to displace an existing operator – trades for marginal blocks between existing licensees might be efficient as demand and technology evolve.

Consumer impact

Direction of causation

It is reasonable to expect a positive correlation across countries between spectrum prices and the prices customers pay for mobile services. Other factors equal, if operators can sustain higher prices for services, for example if retail competition is

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[2] Note that the costs of financing a spectrum holding is only an avoidable cost to the extent that the licence can be sold or leased for a charge.

less intense in some markets than others, this should be reflected in a greater value for spectrum. The direction of causation then runs from service prices to spectrum prices, not the other way around.

Valuation of spectrum

Operators purchase spectrum in anticipation that they can generate returns (relative to the counterfactual without spectrum) to cover the costs of acquiring that spectrum. However, whether spectrum acquisition costs can subsequently be recovered depends on the prices that operators can ultimately sustain within market competition. Like any investment, there is no guarantee that expectations about prices that can be charged subsequently will be correct and that the investment will make a positive return.

Operators expend considerable effort on modelling the commercial benefits of additional spectrum to their business to determine the maximum price they are prepared to pay for it. This involves anticipating what prices they expect to be able to charge for downstream services with additional spectrum and in the counterfactual without it. In such models, anticipated prices for services set spectrum prices, not the other way around. Clearly if an operator had hypothetically been gifted spectrum for no charge, it would not then set prices of its services below the level sustainable in competition, as this would represent a foregone profit opportunity.

Impact on consumers

Put simply, if the ACMA were to set a lower renewal price for spectrum, then, subject to some caveats set out below, we would not expect to see a lower price for mobile services. Why would operators choose to set lower service prices than they could and forgo possible revenue? Therefore, shareholders of operators, rather than consumers, are the primary beneficiaries of low spectrum prices.

ACCAN's views

We note that ACCAN, representing Australian consumers, is unconvinced by the arguments advanced by operators that lower spectrum prices are in consumers' interests.

Impact on operators' costs

Impact on marginal costs

Once spectrum fees have been paid, they have no direct effect on the marginal costs to operators of serving additional customers or providing new services.

Avoidable future charges

One caveat is that in some cases where some spectrum fees are deferred over the course of a licence, there may be the option to return a licence if paying those future charges would not be profitable. However, this option only becomes relevant once spectrum charges are sufficiently large to make retaining a licence unprofitable; again, below that level, we do not expect direct effects on consumer prices. Subject to this caveat, spectrum fees are sunk costs that are incurred anyway and so do not affect the incremental costs to operators of serving additional customers or providing new services.

Financing costs

Operators have raised the issue that spectrum costs might have the potential to increase the need for debt financing, raising the overall cost of capital for operators and so increasing the costs of network investment.

If there is any effect, it is already recognised by benchmarking

First – irrespective of the merits or materiality of this argument– any such effect would *already* have been considered by the benchmarking approach. To the extent that winning and paying more for spectrum in an auction will raise an operator's general financing costs in a manner that can be anticipated, this should be reflected in that operator's willingness to pay for that spectrum. In effect, this is just another cost of holding spectrum that a business case would factor in.

Furthermore, in competitive award processes prices are set by losing bidders, who might reasonably be thought to be relatively more affected by financing issues than stronger winning bidders with higher valuations. If that is the case, any impact on winning bidders' financing costs would already be *over*-corrected within the clearing price. There would be no case for any further additional correction.

Economic rents from structural limitation of competition

Second, within the range of pricing alternatives we are considering here (i.e. within the range of prices broadly consistent with being possible prices of competitive award processes) there is no reasonable policy case for reducing renewal prices because of concerns about the impact on financing costs, as any such impact would be due to a reduction of retained economic rent arising from oligopolistic competition, as we explain below.

Spectrum has value because it is essential for offering services and is in limited supply, leading to a sharp limitation on the number of competing operators. Therefore, competition is oligopolistic. This creates economic rents that determine operators' valuations for spectrum and so prices paid for spectrum at auction. Therefore, even if there was an effect on financing costs caused by increased payments for spectrum, this would be due to a transfer of economic rents created by oligopolistic competition to the state.

The consequences are easiest to see in the *hypothetical* most extreme case where we had a monopoly created by award of some public concession. It would be unreasonable to claim that no payment to the state should be made for that concession because it would raise the monopoly's financing costs. Rather, the concern would be the reverse: that the monopoly might be unreasonably benefiting from artificially reduced financing costs by virtue of excess profits earned from its protected position. These distorted financing costs could in turn lead to inefficient choices by the operator and, more broadly, inefficient capital allocation.

The actual situation is clearly less extreme than this hypothetical example, but similar logic still applies. Spectrum prices reflect oligopolistic rents from a structural restriction of competition due to spectrum scarcity. If those rents were left with operators, this might reduce financing costs, but this is not economically efficient in the broadest sense as it arises from a restriction of competition, albeit an unavoidable one.

In practice, the situation is somewhat more complex, as there are also policy measures in place that seek to boost network investment in certain ways, especially through coverage obligations. The rationale for these policies is typically both that there are external benefits from coverage and that oligopolistic competition between operators may not deliver an optimal level of coverage. Therefore, there is a possible argument that measures to boost network investment further might be helpful, arguably such as lower spectrum charges if this in turn lowered financing costs. However, this fails to recognise that measures such as coverage interventions are *behavioural constraints*. They require outcomes judged optimal by policymakers and so should *already* have balanced costs and benefits. There is no need to take *further* pro-investment measures as these are already considered when those obligations were set.

Materiality of impacts on financing costs

Third, for most operators financing impacts are not likely to be material within the range of alternative plausible prices that we are considering here for several reasons:

- This plausible price range spans reasonable alternative methodologies for estimating a (hypothetical) market price for renewal of licences and intrinsic uncertainty about these estimates. With this range, we are deliberately favouring conversative approaches. Market prices in benchmark data are set by losing bidders within auctions and so do not reflect – nor are likely to even approach – the full economic value of spectrum to licence holders.

- Operators holding existing spectrum licences should have anticipated from the outset that some renewal process will occur as licences approach expiry. From international practice, this is nearly always either re-award through a competitive process, or administrative assignment with prices based on conservative estimates of what prices such a competitive process might determine. Therefore, the need to finance spectrum holdings beyond the initial term of licences can be anticipated in long term business plans.
- It has been suggested that costs of spectrum holdings might specifically cause operators to raise additional debt. However, there is no reason that spectrum be financed through debt specifically. Spectrum costs are just one part of an operator's long-term cost base which can be financed (or re-financed) through some mix of instruments (both debt and equity) as best serves its shareholders' interests.
- Spectrum holdings are assets on operators' balance sheets, in that they could potentially be leased or transferred to other users (and potentially much more easily than other fixed assets such as network equipment).

Revenue and general taxation

Revenue raising as a side-effect of efficient allocation

Some revenue raising is entirely consistent with a primary policy objective of efficient allocation and use of spectrum. Competitive auctions are designed to achieve efficient outcomes. Revenue raising is a necessary side-effect because of the need to create incentives to bid in line with business case valuations. This requires that winners pay at least the opportunity cost of spectrum to losers, otherwise efficient allocation cannot be sustained.

Opportunity cost of unraised revenue

Revenue raising is typically not an objective of spectrum allocation, but equally setting spectrum prices below a reasonable estimate of market value means forgoing spectrum receipts which need to be offset by distortive tax raising elsewhere. This is not to suggest that spectrum prices should be raised above reasonable levels, but equally there is a range where they can act as a relatively non-distortive source of government revenue.

2.3 Choice of central estimator

We now turn to the question of how the choice of estimator affects the relative risks of under- and over-estimating prices. There are number of aspects we need to consider:

- whether an estimator is a good measure *on average* of the central tendency of prices (i.e. the question of possible bias);
- whether an estimator is making best use of available information in a sample to reduce the noise in estimates (statistical efficiency);
- how robust an estimator might be to rogue or incorrect data.

Skewed distribution of prices

For various reasons, benchmark price data tends to be right-skewed, with a longer tail of higher values.[3] This has two important consequences:

- even if we had large samples (which we do not), common textbook central estimators such as the mean, median and mode will not agree;
- there is a particular concern about the possibility of high price outliers raising estimates, as countervailing low price outliers are unlikely.

We ideally want an estimator that is unbiased, efficient and robust, but compromises must be made.

Expected value of estimators

There are many measures of central tendency that could be used to estimate a single price including:

- arithmetic mean;
- median; and

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[3] Benchmark price data is typically not normally distributed. There are several reasons for this. First, if spectrum were not likely to have a material positive value, it would not be awarded. Therefore, we only observe positive prices (and probably only sufficiently positive prices to make running an award worthwhile). Second, the factors affecting valuations (such a market price of services, usage and consumer take-up) combine multiplicatively rather than additively. Indeed, typical benchmark prices are often well approximated by a lognormal distribution for this reason. The detailed implications of prices being lognormally distributed are examined in Annex A.

- geometric mean.[4]

Geometric mean and median

The geometric mean is mathematically equivalent to taking a logarithmic transformation of the prices, taking the arithmetic mean and then transforming that back to a price (by exponentiation). This logarithmic transformation very strongly suppresses the impact of high prices. Similarly, the median is conservative with right-skewed data as it ignores how far above the median high price observations fall.

Expected values

The strong right-skewness of the distribution of prices means that both the median and geometric mean are materially below the mean. We discuss this issue in more detail in Annex A. Assuming a lognormal distribution of prices with similar variance to our sample, the median will on average be about 60% of the arithmetic mean of the sample. The average value of the geometric mean sits between the median and the mean, but much closer to the median for reasonable sized samples.[5] Therefore, both the median and the geometric mean apply very substantial discounts on the mean and so are *already strongly conservative*.

Statistical efficiency and robustness

What is statistical efficiency?

If we hypothetically draw sample data from a population, then calculate some estimator (e.g. geometric mean or median), we would get different results as we take different draws. Ideally, the sample would be so large that the estimates would always be close. However, with small samples there can be considerable variance in estimators around the true population values. We ideally want to use **statistically efficient** estimators that make this variance as small as possible. This makes best possible use of information in the sample about the parameters of the true population distribution.

Robustness of estimators

This is not the only consideration, as we also do not want to make too many assumptions about our population data, as

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[4] In addition, Coleago has suggested using the mode, but this is impractical as a sample estimator. To create a sample mode estimator, observations need to be put into bins or some smoothed version of this created with a kernel function. In either case, the answer is driven by our assumptions. In some cases, prices may not even be unimodal. In small samples, the sample mode may be highly unstable and extremely sensitive to single observations in some situations.

[5] The expected value of geometric mean converges to the expected value of median for log normal data as the sample size grows. See Annex A.

these might prove to be incorrect. In particular, we may want to allow for some proportion of our sample data being wrongly measured without impacting our estimates too much. Estimators with this property are called **robust.**

Intuitively, it is obvious that there will be some trade-off between efficiency and robustness. This is because robustness means that we ignore some information within our sample data, by disregarding or underweighting data far from the centre. However, efficiency requires making use of as much information within that data as possible. Therefore, we need to make an informed compromise. For this reason, we include a more formal analysis, including numerical simulations, in Annex A.

Performance of typically used central estimators

We assess central estimators based on their:

- **robustness** to individual (or small groups of) observations; and
- **efficiency** in using the available data to obtain low variance estimates.

Median is robust, but not efficient

The median is a robust statistic, in the sense that we could increase all observations above (or decrease all valuations below) the median and the answer would not change.

However, the median is affected by any changes to observations that cross the median (i.e. move from the bottom half to the top half of the sample or vice versa). This means that the median can have a high variance as an estimator of the position parameter of a distribution.

This is a particular issue with small samples. If we take our sample, then order observations, we might find that there are large gaps between successive observations in the neighbourhood of the median. As a result, the median may change materially if we move *any* observations from one side of the median to the other. Therefore, whilst it is robust to errors in outliers (far from the centre of the distribution), the median can be sensitive to errors in data close to the median. In comparison, such errors might scarcely affect the mean.

We can see immediately that the median is not an efficient estimator, as it ignores all information about the relative magnitudes of observations and only uses their rank order. Therefore, a lot of information is being thrown away.

Geometric mean can be more efficient

In contrast, the geometric mean uses much more information from the sample, not just the rank order of the observations. However, whilst the impact of high outliers is much reduced by the implicit logarithmic transformation used by the geometric mean, it is more sensitive to outliers than the median. This is because the median entirely disregards high price outliers, whereas the geometric mean compresses them.

On the other hand, if we have errors in our data not just at the extremes, but also in the centre of distribution, the geometric mean might be more robust than the median to such errors, especially within small samples. Care must be taken to consider the full range of problems we may face with data, not just focus solely on high price outliers.

Relative performance

Therefore, we conclude that the median is not necessarily preferrable to the geometric mean as we need to consider not just robustness to outliers, but also statistical efficiency and robustness to other forms of data errors. We provide a full analysis in Annex A, but in large samples with lognormally distributed prices, there is roughly a 25% loss of efficiency in using the median rather the geometric mean.[6]

Hodges-Lehmann estimator

Composite estimator from both median and geometric mean

In this situation, there is a reasonable case for using a slightly more complex estimator that better balances robustness and efficiency than the median or geometric mean do alone.

The Hodges-Lehmann (HL) estimator is calculated by:

- taking all possible pairs of observations;
- averaging these pairs; then
- taking the median of all the pairwise averages.

In this application, we apply the HL-estimator to the log prices, making the same transformations to those implicit in calculating the geometric mean.

We define the geometric Hodges-Lehmann (GHL) estimator by

$$GHL = \exp\left[\text{median}\left\{\frac{\log(X_i) + \log(X_j)}{2} : i \leq j\right\}\right]$$

where X_i are the sample observations. Notice that if there are n observations, the median is taken over $n(n+1)/2$ pairwise averages.

This statistic is a good compromise that is more robust than the geometric mean but more statistically efficient than the median.

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[6] The standard error of the geometric mean is $\sqrt{\frac{2}{\pi}} \approx 80\%$ of that of the median in large samples. See Annex A.

It avoids the problem with the simple median that we might lose robustness to more general forms of data error if there are large gaps between ranked observations in the neighbourhood of the median, as such gaps would be in-filled by pairwise averages in the GHL estimator.

We provide a formal analysis of median, GHL and geometric means in Annex A, including some Monte Carlo analysis of the different estimators' performance. This confirms that in small samples, the GHL estimator has most of the efficiency benefits of the geometric mean, but also most of the robustness benefits of the median.

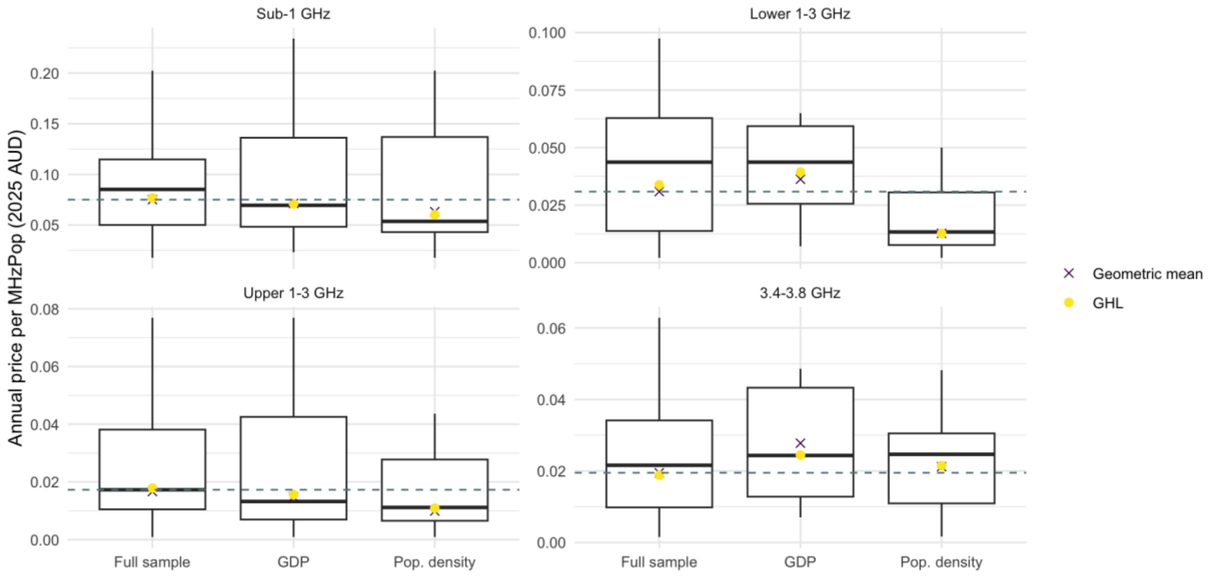
Relationship with Mann-Whitney tests

The HL estimator is closely related to the Mann-Whitney U-test (MW test) already used in the ACMA's methodology, as the two-sample version of the HL statistic (calculating the median of pairwise differences of observations) is the test statistic used for the MW test. Therefore, using the HL estimator (which we call 'GHL' after taking logarithms) is logically consistent and compatible with using the MW test on the logarithms of prices to investigate whether restrictions to subsample should be applied.

GHL applied to ACMA's previous analysis

The figure below reproduces the boxplots used in the ACMA's calculation of single price points (the dashed line is the proposed price) and adds the GHL statistic. It is typically close to the lower of the median and the geometric mean and close to the ACMA's proposed price for the full cohort in all cases.

Figure 1: ACMA single price proposals with geometric Hodges-Lehmann estimates



Note: Dashed line is the single price calculated following the ACMA's Step 6

2.4 Interim conclusion

Geometric mean, median and GHL are all reasonable choices of estimator

The geometric mean, median and GHL estimator are all sensible options for providing conservative estimates of spectrum prices. The ACMA could reasonably select any of these as a preferred central estimator without cohort analysis. All of these estimators are conservative in the sense of being relatively unaffected by high-end outliers. All three estimators can be (in expectation) substantially below the mean.

GHL has some advantages…

To the extent that there are concerns about estimator efficiency and robustness in the small samples, as we have here, there is merit in the GHL estimator. In our view, this has desirable properties (explored in Annex A) in being both reasonably robust and efficient.

…but there is nothing wrong in using the median or geometric mean

Applying the GHL estimator to the full data set (i.e. applying Step 5 with time period filtering but not the Step 6B cohort adjustments) to calculate single price points confirms the ACMA's proposed prices. If there are updates to the data in the future, the GHL estimator is a good methodology for deriving point estimates due to its inherent robustness to various types of data errors.

On the other hand, if the ACMA preferred to use simpler and more familiar statistics, selecting either the median or the geometric mean would also be a valid approach. Selection between the two depends on whether we are more concerned about robustness or statistical efficiency, which in turn depends on the relative quality and quantity of data available. Use of the GHL estimator avoids having to make this choice, in that it retains most of the robustness of the median and most of the efficiency of the geometric mean.

In-built conservatism

All three estimators (median, geometric mean and GHL estimator) *already* give greater weight to over-estimation errors than under-estimation errors. They are all much more conservative (i.e. estimate a lower central price on average) than the simple arithmetic mean. This is analysed in detail in Annex A, where we quantify this conservatism. We see no reasonable case for further increasing the relative weight given to over-estimation errors given that there are policy concerns around – and economic costs to – both under-estimation and over-estimation.

Cohorts to select the estimator

We understand that the ACMA has used cohort selection (i.e. subsamples) as a criterion in its selection between the geometric mean and the median. This reflects some uncertainty over both the appropriate sample and the appropriate estimator to use. We will discuss this in depth in Section 5 below (and formally in Annex B).

For now, we note that there is nothing intrinsically wrong in this procedure as a means to decrease the role of assumptions and to tie together various sources of evidence. However, it is not easy to unpick the statistical properties of this approach. We discuss this fully in Section 5. Anticipating this discussion, we find that using the IQR of the cohort to validate central estimates from the full dataset leads to the validation test often being incorrectly failed, even if there is no underlying difference between the cohort and the full sample. This is especially problematic if the cohort is small.

For this reason, we favour our approach of first focussing on estimator selection, then considering cohort selection only once the choice of estimator is settled. This is simpler and more transparent, being based solely on standard statistical considerations of estimator efficiency and robustness. This confirms the ACMA’s proposed prices based on taking the full sample which are close to our preferred GHL estimator.

Restriction to a cohort

It is still necessary to consider the question of whether there is evidence that the sample should be restricted and only a subsample taken for reasons of greater comparability to Australia. We consider that this is a question best considered *after* settling which estimators are the most appropriate to use. Therefore, we return to the cohort issue in Section 5 below.

3 Time trends

3.1 Fundamental price drivers

Claims of sustained trends

The ACMA has proposed ESL prices based on recent benchmark prices, expressed in real terms. This follows the recommendations in our initial peer review, where we suggested:

- adjusting prices for CPI inflation instead of applying the MSR index; and
- filtering the dataset to only include recent observations (i.e. after a cutoff time), where there was a statistical difference in prices before and after the cutoff time for that band group.

Operators disagree with CPI indexation and that restricting the sample to recent awards adequately deals with trends. Some stakeholders contend that there are historic trends in the price data that are likely to continue, and they would like the ACMA to adjust prices for these trends.

Supply and demand drivers

It is helpful to go back to first principles to consider what drives spectrum prices in the broadest terms. We can identify three broad factors:

- the cumulative spectrum volume available to support mobile services;
- spectral efficiency (bit/s/Hz); and
- consumer bandwidth demand (bit/s) in geographic areas where traffic density is sufficiently high.

Spectrum availability

Spectrum available to mobile network services increases through spectrum awards. These awards typically only occur once there is clarity about harmonisation of spectrum for mobile use and future availability of network equipment and compatible handsets. These awards work in one direction only, increasing total supply of spectrum to mobile in steps.

Spectral efficiency

Technological developments have dramatically improved spectral efficiency measured in achieved bit/s/Hz. In part this is through improved modulation schemes and in part through spatial multiplexing (i.e. MIMO).[7] For example, moving from LTE

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[7] There is an upper limit on the transmission rate of a noisy channel set by Shannon’s law. However, spatial multiplexing escapes this limit.

(4G) to 5G might plausibly increase spectral efficiency by a factor of around 5.[8] These changes mean that a given amount of spectrum can deliver more bandwidth. This decreases spectrum needs for a given target data bandwidth. Again, these changes are in one direction only, as technological improvements will not be rolled back.

Spectrum availability and technology improvements are largely step changes, though deployment of new technologies is progressive. Spectrum valuations might adjust smoothly as expectations adapt and new technology is rolled out, but the effect of these supply-side changes is primarily to cause structural breaks than trends.

Bandwidth requirements

Spectrum needs are set by bandwidth requirements in geographical areas that are capacity constrained. This requires there to be a sufficient density of users within that area. This does not include deep rural areas, where network deployment is constrained by coverage needs.

Need for spectrum is growing both due to increased data use by existing customers, and also new uses such as machine-to-machine applications. Again, this change is one way only.

Net effects of persistent changes in both directions

Therefore, we can see that these three factors are subject to persistent changes and in aggregate can drive spectrum prices up or down. This simple supply vs demand view suggests that there could well be a broadly upward trend caused by bandwidth demand, but superimposed on this would be downward steps caused as new spectrum bands are released and improved technologies become available.

This view – of demand growth tempered by step changes on the supply side – would lead to dynamics for spectrum prices that are significantly more complex than a simple time trend. This is an important observation. We could well see periods (indeed long periods) in which spectrum prices fall, but this cannot be taken to indicate a sustained trend over the longer term. Rather, it is a temporary response to supply-side factors changing, but the underlying growing demand continues.

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[8] *A Comprehensive Real-World Evaluation of 5G Improvements over 4G in Low- and Mid-Bands* (2024), Rochman et al.

3.2 Testing for time trends

Testing for uniform trends

If there were evidence that prices were *uniformly* falling as some operators have claimed, we should be able to:

- cut the data into two subsets (later/earlier);
- test for statistically significant differences between the two sets; and
- find that prices in the later set are significantly lower than in the earlier set.

This approach makes no assumptions about the form of the trend, only that there is a trend.

For such a test to have greatest statistical power (i.e. be most likely to find a trend if there is one), we should avoid creating small subsamples by cutting the sample in the middle. We have largely done this with our test for trends in our previous report, where we applied one-sided Mann-Whitney tests on the claim that spectrum prices have decreased. We suggested 2018 as a common cutoff year across band groups, which roughly splits the sample in half (most sub-1 GHz awards are from 2018 onwards, whereas most 1-3 GHz awards in our sample took place prior to 2018).

In reality, prices may have gone up and down, but that does not establish long-term trends; rather it demonstrates that trends are not stable. Indeed, given the various supply- and demand-side drivers of spectrum prices, we would expect prices to fall in some periods, especially as new technologies improve spectral efficiency for all operators globally. Therefore, given any sufficiently long period, we would expect to see some subperiod with downward price movements. However, this is no evidence of a **sustained** trend.

Alternative trend tests impose additional assumptions but reach the same conclusions

We wish to impose minimal assumptions when testing for changes in spectrum prices over time and we think that the Mann-Whitney test is sensible for this reason. While we presented linear regression lines in our previous report, we have not recommended that they be included formally in the ACMA's methodology.

NERA and Aetha have presented alternative statistical methods – the Mann-Kendall test and the Sen Slope estimator – which may well be more robust than simple linear regression (e.g. there is no assumption on normally distributed residuals). However, these tests still make much stronger assumptions than the simple Mann-Whitney test comparing sub-periods, as they assume a monotonic trend and no serial correlation between observations. In any case, these tests give qualitatively the same answers, namely that prices from 2018 onwards are significantly lower than prices pre-2018 for the Sub-1 GHz and Lower 1-3 GHz band groups, but not for the higher frequency bands.

3.3 Adjusting price estimates for time trends

In cases where we find evidence that prices have decreased over time, there are several ways to account for this when calculating ESL prices. The ACMA could:

- use a subsample of more recent awards to set prices, as the ACMA proposes to do in Step 5;
- fit a trend model and take forecast prices at the end of sample period (remaining *within* the sample period); or
- extrapolate a trend forward *beyond* the sample period and explicitly assume that prices at the time of renewal will be lower than best estimates of current prices due to the trend being sustained.

Stakeholders have suggested various flavours of the latter two methodologies.

We cannot extrapolate trends as future supply side improvements will be limited

The final option (an extrapolated trend) is not appropriate given the various drivers of spectrum prices (discussed above) and that we observe that prices have moved up and down at various points in time. We have significant concerns about extrapolation given that supply-side improvements (greater spectrum supply and spectral efficiency) may be harder to come by in the future. In particular:

- There may be some sub-1 GHz spectrum released from DTT broadcast, but there are no other obvious significant additional sources for mobile spectrum below 3 GHz.
- Spectrum at mmWave frequencies has been released in many countries, but few handsets currently support those bands and fundamental issues remain about handset power consumption at these frequencies.
- 6 GHz may provide additional capacity, but there is potential conflict for this spectrum with demands for WiFi that regulatory bodies are resolving at present.
- 6G may start to become available from 2030 onwards, but standards are still being set. In current TDD bands, spectral efficiency improvements from 6G are likely to be more

modest (~50%[9]) than the improvement achieved by moving from LTE to 5G. The emphasis for 6G will be delivering massive capacity at much higher frequencies.

We recommend using recent awards instead of time trend adjustments

The remaining two methodologies both aim for a current best estimate of spectrum prices at the end of the period covered by the benchmark sample. The ACMA's Step 5 as currently set out – focussing on recent awards in band groups where there is a significant change in prices – is a simple method and is appropriate if there are possible step changes in spectrum supply and spectral efficiency.

Claimed exponential price decay

The alternative is to adjust prices for a timing effect, such as the exponential decay fitted by NERA and Aetha, which is the basis of the claim that ESL prices fail to account for price trends over recent years.[10] An exponential decay model (equivalent to a linear trend in log prices) assumes a constant percentage decrease in spectrum prices year-on-year. It is a *very* strong assumption to extrapolate such an exponential decline in prices into the future, not least as it implies prices becoming vanishingly small in the long run. Such dynamics are not consistent with the simple view of fundamental drivers of spectrum prices we have set out above. This claim of exponential decay in prices for some, but not all, band groups also gives unreasonable implications about the relative pricing of different band groups.[11]

Concerns with time trends

More generally, we have two broad concerns with fitting a time trend and using such a model to adjust prices:

- First, given the drivers of spectrum prices both up and down over time, it is not safe to assume any particular functional form (or even monotonicity) of price trends. There have been movements in spectrum prices up and down over time. Therefore, neither theory nor data support

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[9] *Comparative Analysis of Advantages and Challenges for 5G and 6G Technologies* (2024), Oukaira et al.

[10] If the ACMA were to adjust prices for some price trend, a statistical method would be more appropriate than a return to the MSR index as it allows for hypothesis testing and is calculated using the benchmark data rather than imposing something on it. We have discussed broader issues with the MSR index in our previous report.

[11] There is no significant downward trend in the higher frequency band groups. Suppose that increasing spectrum supply by awarding the Upper 1-3 GHz bands led to a decrease in prices in the Lower 1-3 GHz bands – we cannot expect the prices in the bands with a significant trend to continue to fall below those of the higher band prices, which they eventually would if we assume an exponential decay.

an assumption that there will be a long-term monotonic trend in spectrum prices. We would need to either construct a more complex time series model,[12] or choose a subset of the data over which a simple model is a reasonable fit.

- Second, even if analysis formally found a downward price trend, logically this does not automatically lead to a case for adjusting current prices as the link may not be causal. This is because the timing of spectrum awards is not exogenous. Applying a simple trend adjustment would assume that the price of given spectrum in a given country would be lower, in line with the estimated trend, if it had been awarded later. However, awards of a particular band occur in batches, in line with international harmonisation and equipment development. Within the batch of awards in a particular band, countries where there is greater demand for spectrum might both experience higher prices and award the band earlier (to meet this demand). However, this does not mean that there is a causal link where the price of that specific award would have been lower if the award had taken place later.

We are sympathetic to concerns that more recent benchmarks might better represent current conditions. Indeed, based on the ACMA's existing sample, we have already found that recent prices (from 2018 onwards) are significantly lower than the prices from older awards in the sub-1 GHz and Lower 1-3 GHz band groups, but not in the two higher frequency band groups.[13] Similarly, it is appropriate for the ACMA to restrict its sample to recent awards in the band groups where there has been a statistically significant decrease, as it has set out in Step 5.

However, it is wrong to jump from statistical evidence of difference in prices across sub-periods to the much stronger claim of a sustained monotonic trend in prices. We expect that drivers of spectrum supply and demand will lead to increases and decreases in spectrum prices at different times.

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[12] From the preceding discussion of the factors driving spectrum prices, we can see that prices are likely to be best modelled as a difference between non-stationary processes. Therefore, spectrum prices can be expected to have a complex serial autocorrelation structure. Simple time series modelling (such a regression with a simple time trend) is not adequate to capture these features.

[13] Based on a one-sided MW test.

Furthermore, timing effects within the data cannot be assumed to necessarily be causal.

4 Exchange rates and inflation

4.1 Exchange rates

Several stakeholders expressed a strong preference for using spot exchanges rates over PPP rates. We first explain the differences between these approaches.

Spot rates

The nominal exchange rate, or 'spot rate', is the real-time market price of one currency in terms of another. It reflects factors such as capital flows, interest rates, and market speculation, and is subject to significant fluctuations in the short run. Sudden jumps in exchange rates can be caused by changes in interest rate expectations. For countries that have a significant proportion of GDP attributed to commodity exports, changes in commodity prices can also drive exchange rate changes.

While spot rates are commonly used in international trade, they do not account for cross-country price level differences and are heavily influenced by financial market fluctuations driven by expectations. These fluctuations make using the instantaneous spot rate highly unattractive for benchmarking purposes.

Another issue with applying spot rates is the Balassa-Samuelson effect. It means that productive countries tend to have higher overall price levels, so that using spot rates to make cross-country price level comparison would result in overstatement.

Whilst time-averaging (e.g. a moving average) of spot rates can remove some of the short-term fluctuations, this does not address persistent structural differences such as caused by the Balassa-Samuelson effect which are unhelpful for benchmarking.

PPP rates

A common way to address these issues in benchmarking is to use purchasing power parity (PPP) rates. This equalises price levels across countries by reflecting the relative prices of a common basket of goods and services.[14] Its construction is based on price levels of both tradeable and non-tradeable goods and is not affected by short-term currency rate fluctuations.

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[14] Ofcom chose to use PPP rates over spot rates in its 2025 review of Annual Licence Fees

Construction of the PPP rates is not flawless, and empirical evidence has shown that it may take a very long time for exchange rates to converge to PPP levels.[15] However, in the long run, PPP rates provide a good anchor for exchange rates. For benchmarking purposes, PPP rates should be more reliable than spot rates.

Our recommendation

On the basis that spectrum prices reflect market valuation and forecast for revenues from supplying *domestic* services subject to various input costs – many of which are also domestic – we continue to recommend that PPP rates should be applied to correct for domestic price differences across countries.

The effect of applying PPP rates rather than spot rates is that it pushes the benchmark prices upwards, as it accounts for the fact the Australia is a relatively high-income country. This reflects the relatively higher revenue generated domestically.

Time averaging of spot rates

One point of feedback from the stakeholders is that exchange rates published by the World Bank provides spot rates averaged over a year, which addresses the volatility issue. For Australian Dollars, averaging out this short run volatility might be insufficient, as there have been large changes to AUD spot rates over the last 15 years that we would not expect to be relevant to spectrum valuations.[16] However, volatility is not the only issue we are trying to address. We also need to consider persistent differences driven by productivity differences across countries.

Imported equipment

Another comment from stakeholders is that spot rates play an important role in costs as equipment for 5G rollout is imported at the spot rate. However, it is expected that exchange rate risks in large scale investments in network equipment rolled over time would be largely (if not fully) hedged at the time that a purchase contract for equipment is entered into. Therefore, forward-looking long-run exchange rates are much more relevant than spot rates.

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[15] Kenneth Rogoff, 1996, The Purchasing Power Parity Puzzle, *Journal of Economic Literature*

[16] For instance, if we were using spot rates, everything being converted to AUD would appear relatively lower value in the early 2010s when the AUD was very strong, while COVID-era allocations would appear relatively higher value.

4.2 Inflation

For our analysis, we have used prices adjusted for inflation in two scenarios:

1. Backwards-looking: adjusting previous award prices to today's prices.
2. Forward-looking: inflating future fees to account for predicted inflation over the course of the licence.

Stakeholders have commented on the use of CPI as a measure of inflation and the potential decoupling with spectrum valuations over time.

Rationale

As explored in Section 2, we start with the hypothesis that spectrum value has remained constant in real terms over the period used for benchmarking (unless demonstrated otherwise by the data, which has not been the case). We also expect this to be broadly true over the licence period, as the value of incremental spectrum depends on inputs which change in line with inflation (prices charged to customers and costs of operating).

Therefore, we should be expressing all prices in the same units (2025 AUD). Expressing values in real terms is standard practice in economics. For example, both Ofcom and ISED use country level CPI to adjust prices benchmarks and future prices.

Inflation measures

CPI is generally accepted as a reliable inflation estimate for many purposes. It is a transparent measure and forms the basis of monetary policy. Expectations over CPI inflation are likely to be clearer than over other inflation measures, not least as monetary policy expresses inflation targeting in CPI terms.

In our first pricing review for the ACMA, we outlined why we do not recommend using the MSR index to correct prices either on a backwards- or forwards-looking basis. We do not believe that stakeholders have presented any convincing new arguments for using the MSR index instead of CPI that were not already considered in our previous report.

Alternative inflation baskets

Nor do we believe that communications sector specific inflation measures would be a more suitable means for adjusting prices. The relationship between CPI sector indices and operator profitability or spectrum value is ambiguous and likely varies across goods and services in the CPI basket (e.g. a decrease in the price of complementary goods like mobile phones would not lower spectrum value). One could also need to consider different ways of adjusting for service quality, e.g. whether the service provided by operators should be thought of as a mobile subscription or a unit of data. CPI is calculated using the latter (unit value) approach, leading to lower inflation values to the extent that technical change delivers greater mobile service capability for consumers.[17]

We acknowledge that short term CPI projections (particularly in the run up to the licence renewal) are higher than targeted, though this is more reason to use a broad index which protects against sector-specific shocks. If these price shocks are expected to be transitory, there might be a case for adjusting spectrum prices according to some capped CPI, e.g. at forecast or target inflation. While it is good practice to index ongoing spectrum fees, it would also be reasonable to fix the nominal ESL price at some point in advance of the renewal date to provide certainty for licence fees. The beginning of the two-year application window is probably a suitable time to do so.

In the long run, we expect overall inflation to be near monetary policy targets, but we do not know what relative prices for different goods and services will do over the long term.

Therefore, we have a sound basis for forwarding-looking CPI assumptions, but little basis for forecasting other basket-measures of inflation for subsets of goods and services. Using CPI for adjusting previous spectrum prices (including the high inflation period of 2022-2023) **and** future projections is both more transparent and objective.

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[17] *Price collection: Consumer Price Index: Concepts, Sources and Methods*, Section 8.9, Australian Bureau of Statistics

5 Cohort selection

The ACMA defines two 'cohorts', or subsets of the data, by filtering for countries that meet a threshold based on their similarity to Australia in terms of:

- GDP per capita (at least 70% of Australian GDP per capita and no more than 142%[18]); or
- population density (no more than ten times that of Australia).

Each of these factors potentially affects spectrum valuation, but restricting to a cohort sample significantly reduces the number of observations.

5.1 Cohort methodology

Choosing estimator first, then any cohort restriction second

As discussed above, we can first select a central estimator for the full sample based on statistical properties, without regard to cohort issues. We can then test for cohort differences using standard statistical tests aligned with our preferred central estimator. Therefore, we now return to the question of whether single price estimates are robust to the effect of GDP per capita or population density.

A simplified version of the ACMA's cohort validation approach in Step 6B remains feasible even if it is not used to choose between central estimators, i.e. the ACMA could check whether the selected central estimate for the full sample falls within the cohort IQR and, if it does not, the price could be set by the nearest quartile.[19]

However, we would be concerned if the cohort IQR set the ESL price where the size of the cohort subsample is very small, because the resulting prices would not be robust; in very small

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[18] Cohort weights are less than 1 by construction, being the benchmark country's GDP per capita/population density divided by the Australian value, or the reciprocal of this where the Australian value is lower. The 142% upper bound is 1 divided by the 0.7 threshold. Only Switzerland and Luxembourg have GDP per capita above this. Australia has the lowest population density in the benchmark data, so there is only an upper bound on population density.

[19] Under Step 6B, the cohort quartiles can be price setting if neither the median nor geometric mean falls with both cohort IQRs. Clearly, we must maintain a priority ordering of the cohorts even in the simplified cohort validation approach.

samples, the IQR is not well determined and by relying on very few observations we would simply increase the variability of our price estimates. This could be mitigated by requiring a minimum sample size for the cohort; as a rule of thumb, anything based on a sample of less than 15 observations should be taken as indicatory only (see Annex A.7).

Using cohort IQRs for validation

IQR validation as an implicit statistical test

This validation approach using the cohort IQR can be interpreted as an implicit hypothesis test. We reject our null hypothesis (that there is not a difference between the full sample and the cohort) if our full-sample central estimate falls outside of the IQR of the cohort. However, once interpreted this way, it is not clear what confidence standard is being applied. Therefore, we lack quantification of the strength of evidence being provided about any difference between the full sample and the cohort.

Where the cohort subsample is a small proportion of the full sample, there may be a high probability of Type I errors, i.e. failing the validation test incorrectly. This is because if the cohort is small (either in absolute terms or relative to the full sample) there is uncertainty about the subsample IQR. Even if there is no statistically significant difference between the full sample and the cohort, we might fail the test simply because of IQR being highly variable in a small sample. The validation test would have low statistical significance in the conventional sense, as it is often failed at random.

We have explored this issue formally through Monte Carlo simulations in Annex B. We find that there is nothing wrong with using the IQR of a subsample as a validation test if we had large amounts of data. However, with the sample sizes we have here there is a severe risk of failing the validation test at random. Therefore, this is a poor test with small samples.

Given this, an approach based on formal hypothesis testing is preferrable because:

- the confidence level is explicit and transparent;
- sample size is already taken into account within the test (as the p-value resulting from the test that measures the significance of the evidence of any difference between cohort and full sample); and
- it gives an objective basis for selecting a sample of relevant awards/countries that in turn allows us to be relatively

liberal in including more awards (award inclusion is discussed in the following section).

Statistical test for cohort restrictions

Cohort restrictions based on statistically significant differences

Consistent with the ACMA's approach to band grouping and time trend assessment, we suggest any decision to focus on a cohort should be based on statistically significant differences between observations inside and outside of the cohort. Where price differences are not significant, single prices should be set based on the full sample. Where differences are significant, prices should be set based on the cohort subsample.

A consequence of this approach is that if we add data, we may affect the significance of tests for cohort differences. In particular, it is possible that cohort differences could be insignificant before adding new data, but then are found significant after adding new data. This can then lead to the cohort being used rather than the full sample. Therefore, adding data to the sample might ultimately lead to central estimates being used from a smaller subset.

Testing methodology

Given that there are sound arguments for the use of a Hodges-Lehmann estimator applied to the logarithm of prices (as discussed in Section 2), it is sensible to test for differences within subsamples using the Mann-Whitney U-test. This is a robust non-parametric test.

Order of cohort tests

We have multiple cohorts (GDP per capita and population density) and these are not nested. Therefore, we need to impose some ordering on the cohorts. In Step 6, the ACMA gives precedence to the population density cohort. We think this ordering is reasonable.

As PPP adjustments already correct for income differences to some extent, we expect that population density is likely to have a greater effect than GDP per capita. This is borne out in the ACMA's analysis, where all central estimates fall within the respective GDP per capita IQRs. As discussed below, the income corrections implicit in use of PPP exchange rates justify prioritising population density. However, there is still reason to use the GDP cohort test, not least as GDP may be proxying for various other factors that affect spectrum valuation.

Therefore, assuming the ACMA maintains the same cohort variables as in its previous methodology, we recommend that the ACMA continues to prioritise the population density cohort, by first applying a statistical test based on that cohort, then applying the same test to the GDP cohort. If there is a significant difference found in the population density test, then the GDP test is applied to the population density cohort subsample.[20] If that in turn finds a significant difference, the price is set based on the subsample that is the intersection between the population density and GDP cohorts.

5.2 Population density

We find that there is a statistically significant (at the 5% level) difference in prices in the population density cohort only for the Lower 1-3 GHz bands. There is no significant evidence of different prices for this cohort for the other band groups.

This is essentially the same result as the ACMA finds when applying the Step 6B cohort methodology. The only central estimate that sits outside cohort IQRs is in the Lower 1-3 GHz bands.

Table 1: Difference in prices included/excluded from population density cohort

	Density cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	8	27	0.513	0.630
Lower 1-3 GHz	6	17	0.053	0.030*
Upper 1-3 GHz	7	29	0.271	0.270
3.4-3.8 GHz	14	33	0.747	0.704

** denotes statistical significance at the 5% level, ** denotes statistical significance at the 1% level. Note that use the MW (Mann-Whitney) test is the statistical test we use in this report (for reasons explained in Section 2.3). We provide the t-test results as an indicatory test to show that the results are generally not sensitive to our choice of test.*

However, we should be cautious about filtering by population density based on this one significant result. It results in a

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[20] That is, if the first test finds a significant difference, we then test for a difference between observations (i) in the intersection of the population density and GDP per capita subsamples against (ii) those in the population density cohort but not the GDP per capita cohort.

particularly small subsample of remaining observations (only 6 remain).

p-values are almost certainly over-optimistic

First, we note that the p-values of these statistical tests are calculated based on the null hypothesis that observations are drawn independently from the same distribution. This is very unlikely to be the case in practice, as we would expect a positive correlation between many awards, especially if close in time and from similar regions. This means that the *effective* sample size is smaller than the true sample size and p-values have been underestimated. Therefore, we need to be conservative in interpreting these results and require an appropriate standard of evidence.

In practice, the ACMA could apply a 1% significance level when testing for cohort prices differences. This is conservative in that it applies a stricter threshold than the 5% significance level that might typically be applied when testing for time trends or band grouping. While those might also suffer from over-optimistic p-values, there are further difficulties in defining cohorts, discussed below, that support being relatively conservative in concluding that an effect has been found.

In any case, the results of the test for a decrease in spectrum prices (i.e. using a one-sided Mann-Whitney test) would not be affected by the choice of significance level.[21] If instead the ACMA applies a two-sided test, allowing for an increase in prices over time, it would find a significant increase in the 3.4-3.8 GHz band group at the 5% level, however, this is based on a very small pre-2018 sample and is potentially affected by similar issues with over-optimistic p-values, so we do not recommend filtering for recent awards in that band group. See Annex D.3 for results of these tests.

The "look elsewhere" problem

Furthermore, running multiple tests on different band groups runs the danger of falling into the "look elsewhere" trap,[22] that some significant effects are found purely by virtue of looking repeatedly for different effects. At a 5% significance level, we would reject our null hypothesis in error one time in 20 even if

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[21] Assuming the ACMA considers typical significance levels of 1%, 5% and 10%.

[22] This is the problem of essentially mining data until some significant effect is found, which becomes almost certain to happen if enough tests are run. If a related family of tests are run on the same data, an adjustment (the Bonferroni correction) should ideally be made to the significant level applied to avoid this problem. In our context, this would indicate increasing the evidence standard to approximately the 1% threshold suggested.

there are no actual differences. Applying two cohort tests to four different band groups (so 8 tests) therefore gives us a 34% probability of finding at least one significant result even if there were in truth no effect of population density or GDP per capita. With a 1% significance level this problem of running multiple tests and finding an apparent effect only through random fluctuations is much reduced.

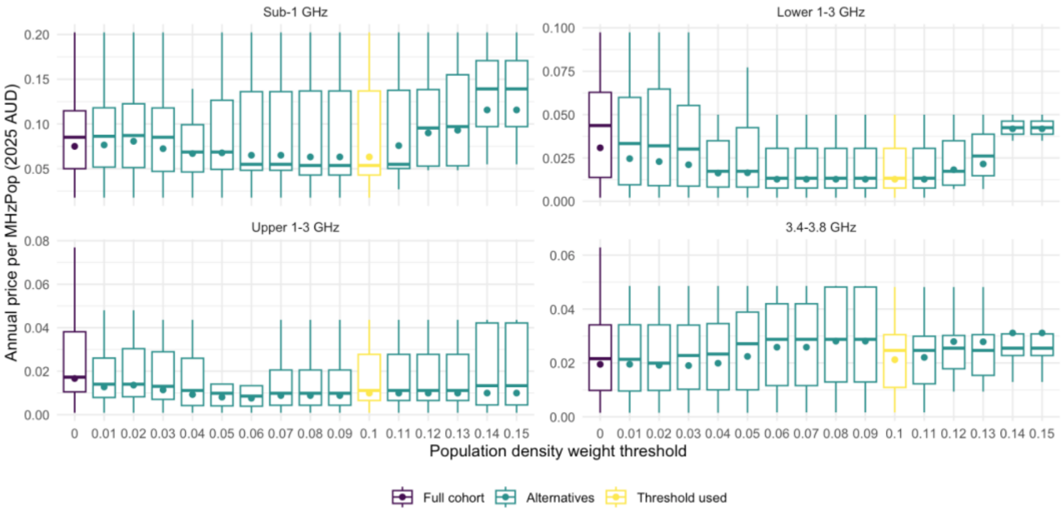
Threshold choice

Second, prices may be sensitive to the level at which the threshold is set. The population density threshold the ACMA applies is 0.1, i.e. the cohort only includes countries with population density no more than 10 times of that of Australia. This results in very small subsamples.

In the Lower 1-3 GHz band group, the cohort IQRs change once the threshold is adjusted to 0.05 or below, as shown in Figure 2. Such a threshold would still exclude 70% of observations, the median population density weight (i.e. the threshold such that half of all observations would fall within the cohort) is 0.031. Countries with roughly the median population density in the sample are Spain, Slovenia and Hungary.

Our fundamental concern with the threshold level is that it leaves us with such a small sample size. Provided that a reasonable proportion of the total sample remains in the cohort subsample, the exact level at which the cohort thresholds are set should not be critical. Again, small samples are particularly problematic in a cohort validation approach because the IQRs of very small samples are effectively arbitrary. On the other hand, the threshold level is less likely to be critical under a hypothesis testing approach, because small sample sizes are taken into account in the test statistics and will make it difficult for us to find strong evidence of significant differences in price.

Figure 2: Price distribution under different density thresholds



5.3 Urbanisation vs population density

Population density may not be the most relevant criterion

Raw population density might not be the most relevant measure of population concentration. There are vast unpopulated areas in Australia that are unlikely be covered in terrestrial networks within a reasonable timescale. Therefore, the headline population density understates the density in areas relevant to spectrum licensing. There are other countries with qualitatively similar population distributions (e.g. Canada or Scandinavian countries), but the size of the sparsely populated areas in each country is not relevant for spectrum valuations unless strongly interventionist coverage obligations are in place.

There is also the potential that, in the context of a cross-sectional analysis across many disparate counties across many continents, population density may stand in for other factors, such as the level of development of a country. If these other factors also lead to a cohort of countries that are similar to Australia, this is not an issue, but the opposite might be the case. We should be cautious about ascribing any differences to population density without adequate controls for other factors.

Urbanisation

As an alternative measure, we could look at the degree of urbanisation in a country, which might capture the prevalence of dense valuable markets and is less affected by swathes of unserved territory. Data published by the United Nations shows that the population of Australia is reasonably concentrated in cities and towns.[23] By this measure Australia sits well within the middle of the distribution.

In general, we think that using population density statistics in a spectrum valuation exercise is sensible, but in the Australian case we suggest using urbanisation instead, because of Australia's extremely low population density that could misrepresent mobile market conditions. Very densely populated countries might not be particularly comparable to Australia (e.g. Singapore, Hong Kong), and these would be excluded from either a population density or an urbanisation cohort. On the other hand, sparsely populated, rural countries lacking valuable urban markets might be equally poor comparators to Australia, but they would only be excluded if we use urbanisation.

If we define an urbanisation cohort (using a 70% threshold as used for the GDP cohort), we see that full sample central estimates sit within the urbanisation IQR, unsurprisingly, given that Australian urbanisation is within the middle of the distribution. We can see from the lower panel of Figure 3 below that restricting the sample by urbanisation yields results broadly consistent with the ACMA's current recommended prices, with the exception of 3.4-3.8 GHz prices, which would be *raised* by this restriction.

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[23] The UN developed the Degree of Urbanization methodology to facilitate robust global analysis. It is a harmonised framework to identify cities, towns, and rural areas in the entire territory of a country, and applies the same population size and density thresholds globally. Combined with gridded population data, the UN provides the *Percentage of Population by Degree of Urbanisation* dataset, among others. Data can be downloaded from https://population.un.org/wup/downloads .

Figure 3: Urbanisation and population relationships

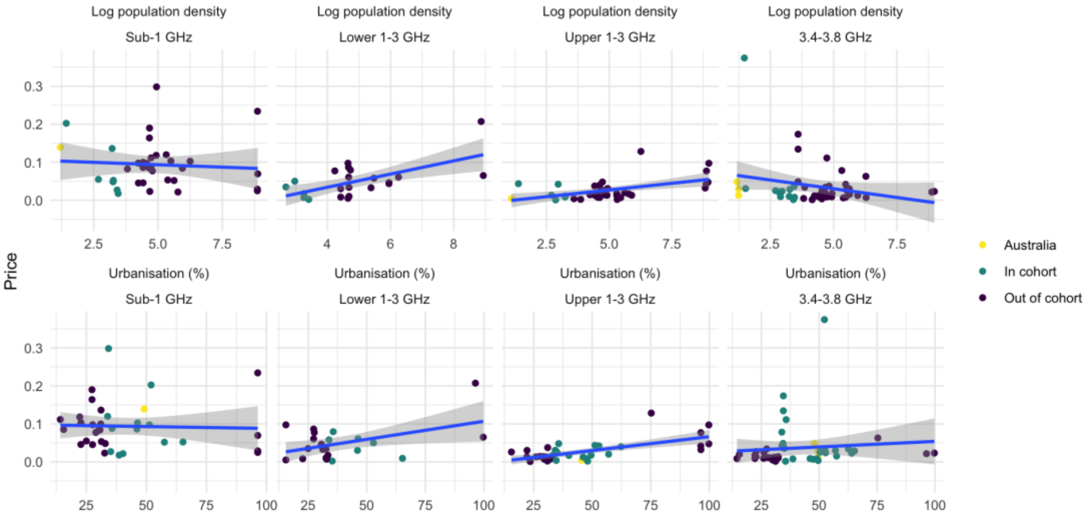
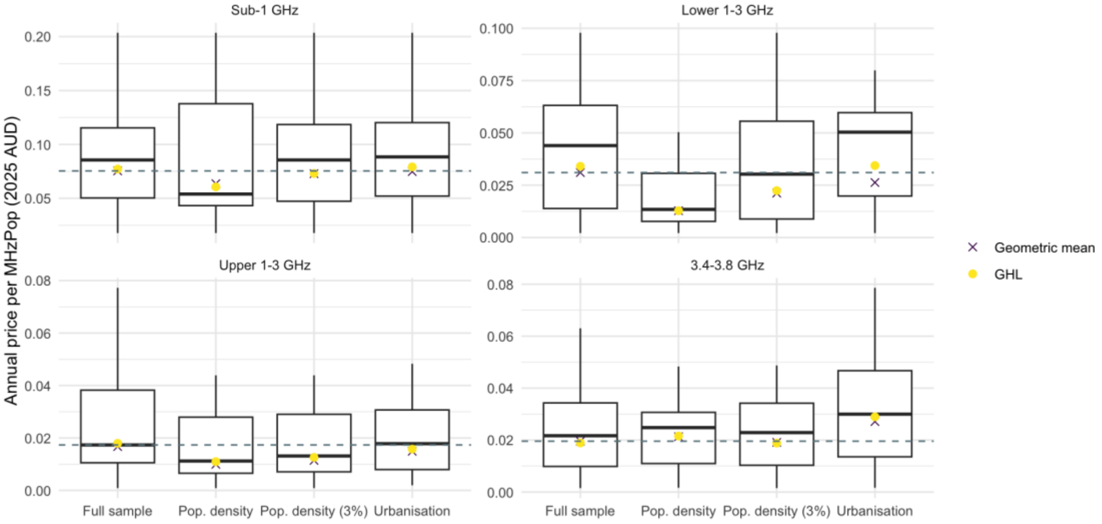


Figure 4: Price statistics by population density/urbanisation cohort



Suggestions of a population density impact are not robust

None of the band groups have a population density price difference that is significant at the 1% level (our suggested conservative threshold for cohort analysis). There is a significant difference in price between the cohort and full sample in the Lower 1-3 GHz bands at the 5% level, but if the ACMA were to either set a lower threshold for the population density cohort, or use the urbanisation measure instead, this would no longer be the case.

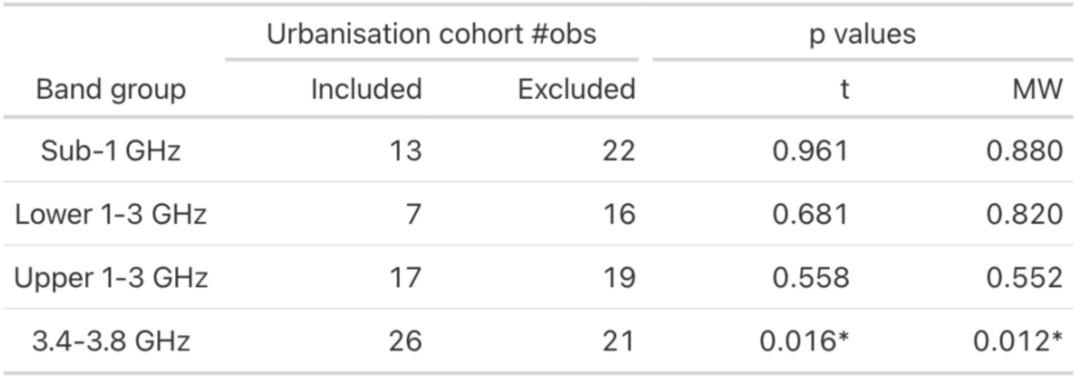
Population density might be correlated with other factors that affect spectrum valuation and it is difficult to test this properly with our small samples. Results are not robust to how we define the cohort (whether by varying the threshold or switching to the urbanisation measure). Therefore, while there is weak evidence of differences between cohorts, this is not robust and we recommend setting prices based on the full sample.

In setting out its formal methodology, the ACMA should require strong evidence of a difference between cohorts, i.e. by applying a 1% significance level, to account for the limited effective sample size (and possible under-estimation of p-values). On balance, we also suggest that an urbanisation cohort would be preferable to using population density. Both proxy for similar conditions affecting network deployment, but urbanisation better reflects that, in areas where mobile networks are or will be deployed, Australia's population distribution is not such an outlier. Both variables aim to find countries with similar network deployment costs (in relevant areas) to Australia and there is no need to include both an urbanisation and population density cohort.

Table 2: Difference in prices included/excluded from population density cohort (lower threshold)

	Density cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	18	17	0.813	0.909
Lower 1-3 GHz	13	10	0.061	0.166
Upper 1-3 GHz	14	22	0.063	0.089
3.4-3.8 GHz	28	19	0.921	0.957

Table 3: Difference in prices included/excluded from urbanisation cohort



	Urbanisation cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	13	22	0.961	0.880
Lower 1-3 GHz	7	16	0.681	0.820
Upper 1-3 GHz	17	19	0.558	0.552
3.4-3.8 GHz	26	21	0.016*	0.012*

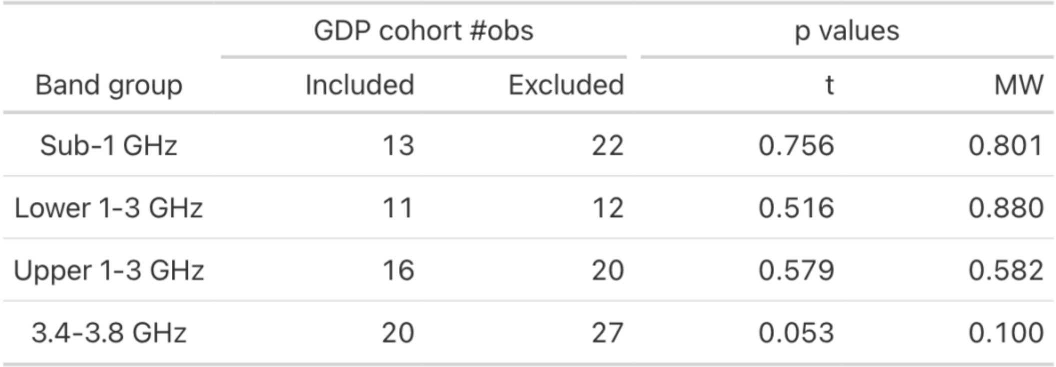
5.4 GDP per capita

Using PPP rates to convert currencies already corrects for income differences across countries to some extent, but it is still reasonable to check against the GDP per capita cohort.

PPP exchange rates correct for the direct effects of income differences and, in otherwise similar countries (e.g. if we were only looking at European awards) this might be sufficient. However, there may also be relevant indirect effects of applying a GDP cohort where this proxies for other factors that affect spectrum value. For example, there could be differences in spectrum value between telecoms markets in countries at different levels of economic development, for which GDP cohorts are a good proxy. In countries where the market is at the earlier stages of maturity, the regulatory framework might be less established, and operators may have greater uncertainty about future revenue streams when valuing spectrum. Therefore, even if PPP rates strip out income effects, it is still worth looking at whether there are remaining effects from GDP differences.

Using the existing sample of awards, we find that the differences between benchmark prices inside and outside of the GDP per capita cohort are not significant, and therefore it does not affect single price estimates

Table 4: Difference in prices included/excluded from GDP per capita cohort



	GDP cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	13	22	0.756	0.801
Lower 1-3 GHz	11	12	0.516	0.880
Upper 1-3 GHz	16	20	0.579	0.582
3.4-3.8 GHz	20	27	0.053	0.100

5.5 Interim conclusion

Country comparability vs sample size

Income and population distribution are likely to affect spectrum valuations and the ACMA's decision to apply cohort analysis is reasonable. Cohorts can potentially improve spectrum value estimates if they select countries that are more similar to Australia. However, this comes at the cost of smaller sample sizes.

Whether there is evidence to restrict to a cohort is a separate question to selection of the most appropriate central estimator. As set out in Section 2, estimator selection should be based on statistical considerations and policy evaluation of the respective consequences of under- or over-estimating the renewal price. Having selected an estimator, we recommend that the ACMA tests for statistically significant differences between observations inside and outside of the cohorts, prioritising the population density cohort, and selects the cohort subsample if it finds a significant difference.

This recommendation is not contingent on adopting the GHL estimator; any of the three estimators discussed above (GHL, geometric mean, or median) could be used in a similar way.

However, there are practical difficulties to applying this analysis, particularly with small numbers of observations within cohorts. These are most acute for the population density statistics, as simple population density might not reflect the areas in which mobile networks will be deployed. The ACMA could replace the population density cohort with an urbanisation cohort.

Conservative approach

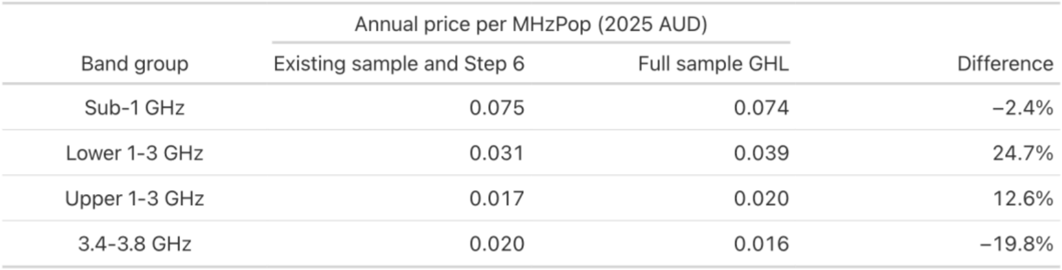
In any case, we recommend that the ACMA takes a conservative approach to cohort analysis, by testing for statistical differences between prices inside and outside of the cohort using a 1%

significance level. This is because (i) award prices are unlikely to be (statistically) independent and test statistics are likely over-optimistic and (ii) we are running multiple non-nested tests and we need to be cautious about finding a significant result simply due to the number of tests run.

One cohort test needs to be applied before the other. Irrespective of whether the ACMA chooses to use population density or urbanisation, this cohort test should be applied before the GDP per capita test, because using PPP rates (partially) corrects for income differences.

Up to this point of our report, we have focused on possible amendments to the ACMA's methodology, which we have applied to its existing benchmark sample to provide comparability with our previous report. Based on this data, we find no statistically significant differences between the cohorts and we would therefore recommend setting prices based on the full-sample GHL estimates.

Table 5: Results of applying the revised methodology to the existing sample



	Annual price per MHzPop (2025 AUD)		
Band group	Existing sample and Step 6	Full sample GHL	Difference
Sub-1 GHz	0.075	0.074	−2.4%
Lower 1-3 GHz	0.031	0.039	24.7%
Upper 1-3 GHz	0.017	0.020	12.6%
3.4-3.8 GHz	0.020	0.016	−19.8%

6 Data selection

6.1 Exclusion of observations

Several stakeholders have provided feedback regarding data selection. The main contention is that certain awards are outliers which push up ESL prices and should be excluded.

Competitive awards

Benchmarking analysis assumes that competitive awards of comparable spectrum provide useful information in estimating market value. If bidders bid according to their valuations, auction prices are set based on bidder's values for marginal lots, whereas if prices were set administratively, they tell us nothing except a soft lower bound on valuations. Therefore, awards should be excluded if they are not competitive awards of comparable spectrum.

Reasons for exclusion

Therefore, the ACMA has excluded awards with:

- material amounts of spectrum going unsold (these awards are **not competitive** and market value would likely be below reserve prices);
- restrictions on the use of the spectrum to specific use cases (the licences on offer are **not comparable** as they *could not* be held by the operators holding existing licences in Australia); or
- the auction was a residual award of unsold spectrum from a previous auction where the remaining licences have material limitations with regards to geographic coverage, bandwidth offered[24] or licence duration, such that the prices are **not comparable** to national benchmarks.

There may well be good reasons for excluding further awards, but they generally fall into one of two cases:

- **measurement issues**, where sufficient information to calculate award prices is unavailable or we have clear reason to expect it is incorrect (e.g. awarded bandwidth

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[24] This does not necessarily rule out all residual awards. If licences are only available in remote regions, or with short durations (insufficient to support investment) to co-terminate with licences from the original award, these do not give relevant price estimates. On the other hand, spectrum might go unsold in an early award (relative to international benchmarks in the band), but then market conditions develop and a future award of *comparable* spectrum licences could yield a relevant benchmark price.

numbers that exceed the total amount of spectrum available in a band); or
- **objective characteristics** of benchmarks that can be used to group observations and test for statistical differences between prices in different groups.

Sensitivity checks

It is difficult to define criteria that give clear cut answers for every award, and, inevitably, there will be a small number of cases where it could be argued one way or the other whether including an award is consistent with these principles. However, we do not think any such decisions materially affect final prices. Annexes C and D provide our reasons for excluding certain additional awards along with sensitivity analysis on the effect of including them.

The ACMA has been transparent regarding its benchmarking data, provided opportunities for stakeholders to comment on the data, and revised its sample in light of these comments. This mitigates the risk of measurement issues affecting ESL prices.

Presumption of inclusion

We follow the general statistical principle that all observations should be included unless there is good reason for exclusion according to the criteria above. Exclusion for these reasons does not require any detailed statistical testing, or even knowledge of the award prices. Table 18 in Annex C outlines how we have implemented these rules practically.

The ESL pricing methodology contains several steps that segment observations based on **objective characteristics**, namely when:

- grouping bands;
- splitting observations by time period; and
- constructing cohorts based on population density and/or GDP per capita.

This selection of subsamples is based on clear objective criteria. Therefore, it is a much more transparent and robust than a subjective case-by-case assessment of which awards are ‘relevant’.

Outliers

We note Coleago’s comments that we have removed outliers in several of our previous benchmarking reports. One of our main objectives in doing so was to catch errors in our data to ensure results were not driven by measurement error. We make continued efforts to improve both the quality of our data and the robustness of our statistical analysis and as such we see no reason that we should be bound to a particular approach that we have taken in the past. In our work for national regulators we have moved away from an approach of using simple means with pruning out outliers to the use of estimates that are more robust to outliers, reducing the need to eliminate outliers. This reduces the need for debateable exclusion of observations and allows better use to be made of the information contained within the data.

We do not believe that the ACMA needs to exclude 'outliers' from the data. Instead, as discussed above, it should select statistics that are robust to individual observations and give conservative estimates of market value.

6.2 Sensitivity analysis

Jackknife analysis

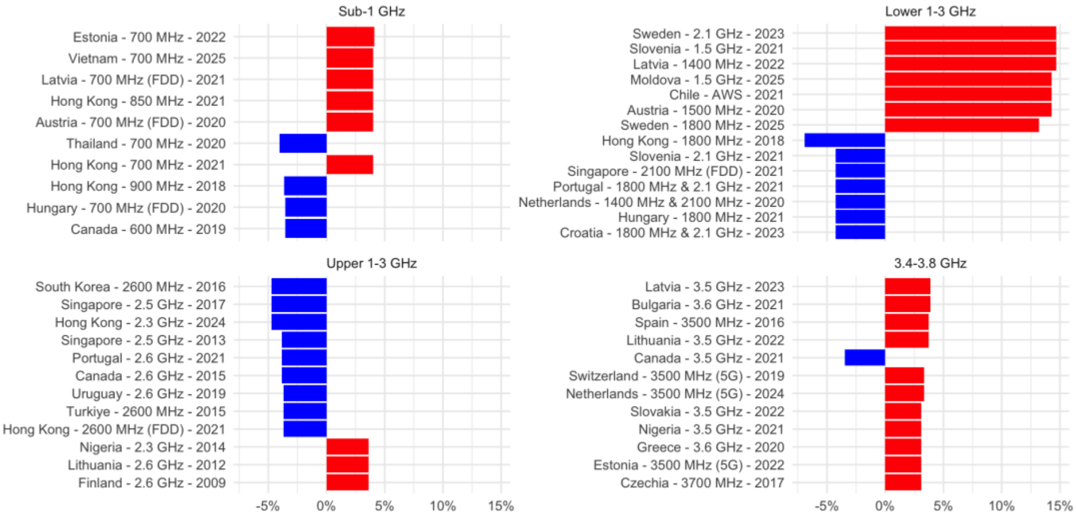
We have performed some sensitivity analysis to test whether the ACMA's methodology and our proposed amendments are in fact robust to the effect of individual observations. We use a 'jackknife' analysis that removes benchmark observations one-by-one and recomputes the single price statistics to see how much they change.

The figure below shows the percentage changes in our geometric Hodges-Lehmann (GHL) estimator when removing individual observations. This is a good measure of the sensitivity of the overall results to particular observations. We show the top ten awards for each band group, by the absolute value of the change (more than ten awards when there are ties).

The GHL measure moves both up and down and the size of the changes is typically less than 5%. We highlight that the Canadian 3.5 GHz award – pointed to by some stakeholders as an extreme outlier – has an effect comparable in size but in the opposite direction to several other observations in the same band group. This clearly demonstrates that our approach (e.g. using logarithmic transformations) is effective in controlling the effect of high price awards.

Further details and results for other statistics (median, geometric mean, and the single prices as per Step 6B) are given in Annex D.

Figure 5: Change in GHL statistic when removing individual observations



At this point we use the observations in the dataset previously published by the ACMA. Therefore, this graph includes the Moldova 1.5 GHz award, which, on review, has been excluded because a large amount of the spectrum on offer went unsold.

SDL spectrum

The greatest effects of individual awards are all in the Lower 1-3 GHz group, where removing any of the seven most extreme awards would *increase* the central price estimate. The majority of these are awards for supplementary downlink (SDL) spectrum, typically in the 1.4 GHz and 1.5 GHz bands, which is combined with FDD spectrum to increase downlink capacity. These benchmarks have different objective characteristics to others in the band group, having a different band and mode. This spectrum would not be of use to an operator without other FDD spectrum.

In our previous report, we noted that there is a statistically significant difference between prices for SDL spectrum and prices in the other Lower 1-3 GHz bands.[25] Given this and their relatively large effect on single price estimates, we believe that there are grounds for the ACMA to remove SDL awards from the band group. However, this change is not essential, as the ACMA has already taken broader considerations (beyond statistical tests) into account when constructing band groups, e.g. when keeping 3.4-3.8 GHz separate from Upper 1-3 GHz.

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[25] Table 6 on p 48 of our previous report shows 1500 MHz prices are significantly lower than other Lower 1-3 GHz band prices. Density plots, included in Annex D of this report, show a visible difference between SDL prices and 1800/2100 MHz prices.

Jackknife by country

We have also looked at the effect of removing awards country by country, which again causes small differences in price in both directions. Of these, by far the largest effect comes from removing Swedish awards in the Lower 1-3 GHz bands; without those two awards, the GHL price estimate would be over 20% higher. Otherwise, the larger effects come from countries with multiple awards in the same band group, but the effects are small – removing a country changes the central price estimate by less than 10% (except Hong Kong in the Upper 1-3 GHz bands or cases shown above where individual award effects are greater).[26] This gives no evidence that there are outliers that should be removed, but does reflect the ACMA's approach to weighting observations. It has taken the balanced approach of aggregating prices across bands in a single award, but keeping awards in the same country at different points in time separate, which is reasonable.

6.3 Additional awards

Few additional awards are reasonable to add

It is generally good practice to include additional competitive awards of comparable spectrum where the data is available. Stakeholders have provided a list of awards to include in the dataset, to which we have added other awards from 2025 now held in our Spectrum Awards Database (SAD). However, not all of these awards can be added to the sample because they were uncompetitive, licences are not comparable to the Australian context, or because key information needed to calculate benchmark prices is lacking.

Adding these has little impact

Including the remaining observations, we find that the additions make very little difference to central price estimates, except in the 3.4-3.8 GHz bands. All suggested additional awards that we have excluded are listed in Annex C, along with the reasons that we have excluded them. We have also carried out jackknife sensitivity analysis to assess the effects of excluding each award on the central price estimates, available in Annex D.

The number of observations and the resulting GHL statistics are given below. These effects are generally small (i.e. less than 5%).

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[26] Full results are in Annex D, but the largest effect on GHL prices for each band group are: removing four Hong Kong Sub-1 GHz awards leads to a 5.3% increase; removing two Swedish Lower 1-3 GHz awards leads to a 23.5% increase; removing three Hong Kong Upper 1-3 GHz awards lead to an 11.6% decrease; and removing three US 3.4-3.8 GHz awards leads to an 8.1% decrease.

For the revised sample, we use the data from the ACMA +additions columns, which includes:

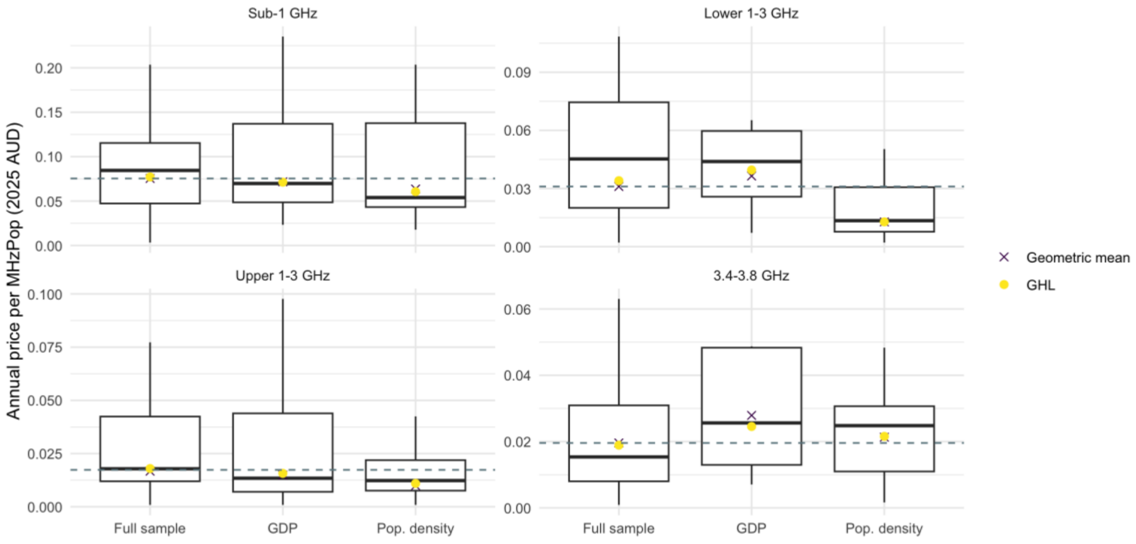
- all observations already included by the ACMA;
- additions provided by NERA/Aetha if they meet the criteria discussed above;
- a small number of additional 2025 awards from our SAD;
- minor corrections to these awards;[27] and
- SDL awards remain in the dataset.

Table 6: Annual price per MHzPop GHL statistics (2025 AUD) by sample

	#Obs				GHL price				
Band group	ACMA	+Additions	+Excl. suggestions	+Additions ex SDL	ACMA	+Additions	+Excl. suggestions	+Additions ex SDL	Cumulative % Change
Sub-1 GHz	35	39	44	39	0.077	0.074	0.067	0.074	−4.5%
Lower 1-3 GHz	23	26	27	20	0.034	0.039	0.041	0.052	52.5%
Upper 1-3 GHz	36	44	52	44	0.018	0.020	0.017	0.020	8.8%
3.4-3.8 GHz	47	55	62	55	0.019	0.016	0.014	0.016	−17.0%

Cumulative % change column is the difference between the 'ACMA' column (the sample used by the ACMA in its updated preliminary views on pricing document) and the '+additions excluding SDL column'. The latter does not include excluded suggestions.

Figure 6: ACMA single price proposals with geometric Hodges-Lehmann estimates - revised sample



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[27] This only affects the 2021 Portuguese 3.4-3.8 GHz benchmark.

Interaction with cohort analysis

The sensitivity analysis described above is conducted prior to applying any cohort analysis. As discussed below, differences between cohorts are not statistically significant, but this could in principle change if we included additional awards.[28] In effect, we might add awards to then exclude them at the cohort selection step.

For the avoidance of doubt, we have not looked at the impact on final prices to determine our inclusion or exclusion of awards. Nevertheless, it is helpful to notice that including *lower price awards*, if they fall outside of the GDP or population density cohort subsamples, *could increase final prices once the cohort analysis is revised to take into account the additional data*. In particular, the GDP cohort prices in the 3.4-3.8 GHz bands are higher than the full sample prices, based on the ACMA's existing sample. By adding low price awards in countries with GDP per capita well below Australia's, we can cause this difference to become statistically significant, leading us to select the GDP cohort price.

Indeed, if we run the cohort analysis on the revised sample, we find that:

- there is insufficient evidence to restrict the sample to the population density cohort for any band group, as the differences are not significant at the 1% level (nor are the differences robust to using the urbanisation statistic or a different population density threshold); but
- the difference between 3.4-3.8 GHz prices inside and outside of the GDP cohort is significant at the 1% level, therefore the price can be set based on the GDP cohort subsample. In other band groups, the difference is insignificant.

We should not be surprised by greater heterogeneity in prices in the 3.4-3.8 GHz bands compared with lower frequency bands. The band is both a pioneer 5G band and has uses for fixed wireless access in rural areas. Distinct use cases might have very different values and countries with different GDP levels might have a different mix of these use cases, or simply much weaker demand for 5G services.

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[28] This also applies to the time trends test. Collation of a benchmarking sample is the first step in the process and we also need to test for time trends (as set out in Step 5) on the revised sample. Doing so gives the same results – a significant decrease in price after 2018 for the Sub-1 GHz and Lower 1-3 GHz, but not the other band groups – for the revised sample.

Below we include the results of the cohort tests. For completeness, we include all options for population density/urbanisation testing shown above, even though we recommend using urbanisation only.

Table 7: Difference in prices included/excluded from population density cohort – revised sample

	Density cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	8	31	0.837	0.772
Lower 1-3 GHz	6	20	0.044*	0.019*
Upper 1-3 GHz	8	36	0.170	0.151
3.4-3.8 GHz	14	41	0.244	0.278

Table 8: Difference in prices included/excluded from population density cohort (lower threshold) - revised sample

	Density cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	21	18	0.372	0.512
Lower 1-3 GHz	14	12	0.034*	0.085
Upper 1-3 GHz	19	25	0.021*	0.030*
3.4-3.8 GHz	30	25	0.949	0.967

Table 9: Difference in prices included/excluded from urbanisation cohort - revised sample

	Urbanisation cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	15	24	0.603	0.853
Lower 1-3 GHz	8	18	0.850	0.935
Upper 1-3 GHz	22	22	0.853	0.917
3.4-3.8 GHz	29	26	0.090	0.043*

Table 10: Difference in prices included/excluded from GDP per capita cohort - revised sample

	GDP cohort #obs		p values	
Band group	Included	Excluded	t	MW
Sub-1 GHz	13	26	0.742	1.000
Lower 1-3 GHz	11	15	0.748	0.878
Upper 1-3 GHz	17	27	0.702	0.633
3.4-3.8 GHz	21	34	0.001**	0.003**

The GHL price estimates for each cohort in the revised sample (including additional awards suggested by stakeholders) are given in the table below. Applying the ACMA's methodology, with our proposed amendments, to the revised sample, gives us prices:

- slightly below the ACMA's initial proposals for a single price in the Sub-1 GHz bands;
- above the initial proposals in the 1-3 GHz bands, because of the inclusion of additional higher price observations; and
- above the initial proposal in the 3.4-3.8 GHz bands, because we find evidence to select the GDP cohort rather than the full sample.

Table 11: Cohort GHL estimates - revised sample

	#Obs				GHL price			
Band group	Full	GDP	Pop density	Urbanisation	Full	GDP	Pop density	Urbanisation
Sub-1 GHz	39	13	8	15	0.074	0.071	0.061	0.071
Lower 1-3 GHz	26	11	6	8	0.039	0.040	0.013	0.043
Upper 1-3 GHz	44	17	8	22	0.020	0.018	0.012	0.018
3.4-3.8 GHz	55	21	14	29	0.016	0.026	0.022	0.022

These prices are provisional, as the ACMA plans to include data on further awards that take place prior to the renewal window, as discussed below.

6.4 Price updates

Need for a cutoff time

We agree that including latest award prices in the benchmarking dataset would help the resulting price reflect the latest market valuation. Updating the benchmark dataset with new competitive awards is encouraged. However, there are diminishing returns to updating the analysis ever closer to licence end dates, as there will be fewer potential new awards to consider and so the impact on conclusions will be ever smaller. However, it is also important to recognise that some steps of the methodology entail step changes once an evidential threshold is reached, such as if significant evidence is found to restrict to a cohort. At present, we are not close to the threshold of any of these tests, so there is no particular reason to expect a small amount of new data to trigger such a change.

Given the diminishing returns from updating ever closer to the renewal window, there should be a clear cutoff time *prior to* the renewal window to provide operators certainty in renewal prices. In keeping with this, the ACMA has proposed a cut-off of six months prior to the renewal application window, which itself is two years prior to the start of the new licences. There is no single correct time at which to put this cutoff, but the ACMA's proposal is reasonable. Any later than this would not be practical, especially as the ACMA intends to consult on updates to its benchmark sample.

There is also significant merit in finalising proposed nominal prices for renewals (even if inflation corrections are subsequently applied mechanistically) sufficiently early such that any disputes over the conclusions can be resolved without risk to the overall deadline set by licence expiry. This reduces the risk of needing interim measures to roll over licences if there were a live dispute.

Stable methodology with any new data

Applying updates to the benchmark sample, and using up to date inflation and PPP statistics rather than forecasts, could improve the accuracy of the ESL prices. However, as the ACMA recognises, there is some uncertainty at this stage as to whether prices will increase/decrease, whether time effects might be uncovered,[29] and on the availability of data. This uncertainty can be mitigated to some extent by giving any necessary clarifications over the methodology for award selection and for calculating benchmarks (including the sources used for macroeconomic data) now. Any subsequent consultation then needs only concern the accuracy of new award data and comment on any data omissions, not changes to the analytical methodology. New awards should be identified from public sources (industry news outlets and regulators websites), just as the ACMA has already done, and then they can be added to the sample if they meet the criteria discussed above.

For the early renewals, it is unlikely there will be enough new awards to substantially affect resulting prices. We would recommend that the ACMA uses the proposed methodology where possible and there is every reason to think that this can simply be reapplied. However, equally if a new reason arose to deviate from it, this would need to be considered on its merits at the relevant time. Therefore, the proposed methodology in this report is general, but we make no claim that it is universal.

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[29] If there are enough new awards, the cutoff for testing for price differences between new and old awards should be updated (again splitting the sample in half) rather than fixing 2018 onwards as the definition of 'recent'.

Payment timing issues

There is also the question of adjusting prices *within* the award window to ensure fairness for operators who apply at different times and possibly incentivising early application and payment. We consider this is a minor issue, but there are two broad options:

- fix a constant price that applies to all operators whenever they apply/pay; or
- apply a discount to this price for early application/payment, using some assumed discount rate and the application data for each operator.

We expect the discount rate in the latter case would likely be set conservatively (for example at the short-term rate for government debt, reflecting the benefit to the government of early payment). In this case, early payment would likely be commercially unattractive, so of limited importance.

For simplicity, we suggest applying a constant price, irrespective of application timing. This is known to all operators at the start of the application window and therefore treats them fairly. This may well give incentives to pay as late as possible before the cut-off date for renewal, but we see no particular problem with this as the ACMA can simply set an appropriate cut-off date.

7 Conclusions

Summary of recommendations

We find that the ACMA's benchmarking methodology gives fair, neutral estimates of the market value of spectrum and is a suitable way of setting ESL prices. The ACMA has diligently implemented our previous recommendations for modifications of its methodology and we are able to reproduce the ACMA's results.

Central estimator and cohorts

In the interests of simplicity and transparency, we have proposed an approach of splitting of the ACMA's Step 6 to consider price estimation separately and in advance of cohort issues, by:

- taking central price estimates using the geometric Hodges Lehmann statistic; and
- restricting to cohort subsamples only when there is strong evidence of significantly different prices inside and outside of the cohort.

This approach provides a good test of the robustness of the ACMA's conclusions without any conflation of the questions of how best to estimate prices and which observations should be used. This approach results in only a modest change in suggested ESL prices.

This approach is intrinsically conservative in that it applies a logarithmic transformation to prices, supressing the effect of high price observations relative to using the arithmetic mean.

Our views on price trends, exchange rates and inflation adjustments are largely unchanged from our first report. We do not see evidence of a sustained price trend that would justify explicit adjustments to ESL prices. Using PPP rates and working in real prices is well aligned with best practice in economics.

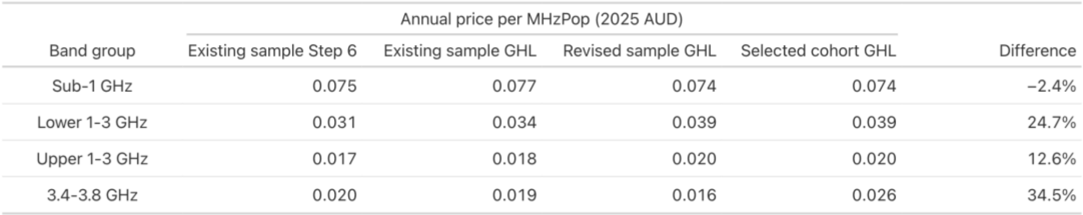
Sample selection

We have carried out a more thorough review of the benchmark sample, which both improves transparency on why some awards have been excluded and demonstrates that individual award inclusion/exclusion decisions do not affect ESL prices. Removing high price awards based on the assertion that they are outliers would risk biasing prices downwards, whereas the ACMA's approach is neutral.

We recommend adding additional awards, suggested by stakeholders or from our SAD, where they are competitive awards of comparable spectrum and the relevant information on these awards is publicly available. Expanding the sample has a greater effect on prices than revisions to the methodology, notably because with a larger sample, there is evidence of a significant difference in 3.4-3.8 GHz prices in the GDP cohort compared with awards of the same bands in other countries.

There is a reasonable case that SDL awards could be removed from the Lower 1-3 GHz group, which would result in much larger increases in prices in that band group. Removing these awards is not essential, and we include them in our recommended prices, summarised below.

Table 12: Summary of price recommendations



	Annual price per MHzPop (2025 AUD)				
Band group	Existing sample Step 6	Existing sample GHL	Revised sample GHL	Selected cohort GHL	Difference
Sub-1 GHz	0.075	0.077	0.074	0.074	−2.4%
Lower 1-3 GHz	0.031	0.034	0.039	0.039	24.7%
Upper 1-3 GHz	0.017	0.018	0.020	0.020	12.6%
3.4-3.8 GHz	0.020	0.019	0.016	0.026	34.5%

Comparison with other regulators

UK 2025 review

In 2025, Ofcom reviewed its Annual Licence Fees (ALFs) charged to UK operators for use of the 900 MHz, 1800 MHz and 2100 MHz bands.[30] The methodology relies primarily on UK auction prices rather than international benchmarks. Benchmark prices are only used to determine relative prices between bands, as the licences being renewed are in different bands to those awarded by Ofcom in 2018 and 2021.

For the 900 MHz fees, Ofcom takes the prices paid in the UK 2021 auction of 700 MHz and annualises prices. This auction was conducted in the same year as the Australian 850 MHz and 900 MHz auction, which resulted in much higher prices when compared to the UK auction.[31] If we used this same methodology to calculate the Sub 1-GHz fees, we would end up

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[30] Statement: Review of Annual Licence Fees, Ofcom

[31] Sub-1 GHz prices were 63% lower in the UK than in Australia in 2021, while bandwidth weighted average 3.4-3.8 GHz prices were 30% lower in the UK than Australia across the 2018 -2023 awards.

with annual fees of $0.14/MHz/pop (almost double the ACMA's proposals).

Upon consultation with stakeholders, Ofcom chose to reduce its proposed ALFs by 5%. This is a very conservative approach, applied despite Ofcom engaging with each of the suggested reasons for a reduction in spectrum valuations since the 2018 and 2021 auctions and not being convinced that any of them (individually) had lowered spectrum valuations.

Canadian annual fees

ISED also reviewed their annual licence fees charged to current licence holders across all bands below 10 GHz in 2025.[32] The annual licence fees are based on total holdings across Canada in the relevant bands.

To determine the fee level, ISED considered renewal fees in jurisdictions with similar policy objectives to that of ISED.[33] This included Australia, the UK and several other countries in Europe. ISED found an average of the fees to be AUS $0.023/MHz/pop and set this as the marginal spectrum renewal price.[34] ISED reviewed prices paid at auction, but *"this data did not directly influence fee benchmarks given the influence external factors can have on auction results"*.[35] In contrast, the ACMA's approach is based on auction price benchmarks as these give a more reliable estimate of market value.

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[32] *Decision on a Fee Framework and Amendments to Conditions of Licence for Certain Spectrum Licences Used to Provide Commercial Mobile Services Below 10 GHz*, ISED

[33] *"Estimating the forward-looking market value of spectrum, accounting for a portion of turnover earned by operators and incentivizing the efficient use of spectrum"* (ibid Annex A - Methodology)

[34] Below 1.8 billion MHzPop aggregate spectrum holdings, lower marginal prices apply. A national operator only needs approximately 45 MHz to reach this threshold, therefore the highest marginal price applies to the majority of national operators' spectrum holdings.

[35] *Decision on a Fee Framework and Amendments to Conditions of Licence for Certain Spectrum Licences Used to Provide Commercial Mobile Services Below 10 GHz*, ISED, Annex A – Results

Annex A Central estimators

In this annex we investigate the performance of various central estimates under the assumption that underlying prices X are log-normally distributed (or with variations around these assumptions). In particular

$$\log(X) \sim N(\mu, \sigma^2)$$

The population mean is then $E(X) = \exp(\mu + \sigma^2/2)$.

A.1 Mean vs median and geometric mean

Draw a sample of n independent observations from this population. The sample has geometric mean G and median M.

The median of the log-transformed prices is the same as the median of the prices (as this is an order-preserving transformation). From symmetry of the underlying normal distribution,

$$E(M) = \exp(\mu)$$

This understates the population mean $E(X)$ by a factor of $\exp\left(-\frac{\sigma^2}{2}\right)$.

The geometric mean is the antilog of the arithmetic mean of the log prices. Therefore,

$$\log(G) \sim N\left(\mu, \frac{\sigma^2}{n}\right)$$

and so G is also log-normally distributed. Its expectation is therefore

$$E(G) = \exp\left(\mu + \frac{\sigma^2}{2n}\right)$$

We always have $E(M) < E(G) < E(X)$. Both the median and the geometric mean are downward biased estimates of the population mean. For large samples, $E(G)$ tends to $E(M)$ as the sample size increases, so G is an asymptotically unbiased estimator of $\exp(\mu)$.

A.2 Interpreting the uncertainty parameter

To roughly understand the scale of this conservatism, it is helpful to interpret the uncertainty parameter σ in terms of the spread of the underlying prices.

Given a normal distribution with SD σ, $\log(X)$ will be within $\pm 2\sigma$ of the mean about 95% of the time. Therefore, if prices spanned one order of magnitude (i.e. a factor of 10) and this corresponding to log prices being within $\pm 2\sigma$ of the mean, we would have $\sigma \approx \frac{\log(10)}{4} = 0.58$. This gives $\exp(\sigma^2/2) \approx 1.33$, so the mean would on average be 33% higher than the median or (in larger samples) geometric mean.

For our data we have $\sigma \approx 1$ (though this varies across band groups), so the median would be expected to be about 64% of the mean.

A.3 Estimator performance

To assess estimator performance, assume that n draws of X in the sample are independent. This is very likely not the case, with observations being positively correlated. Within the assessment below, this mean that variances of estimators that are larger than calculated. We can think of this as the effective sample size being smaller than the actual sample size.

As $\log(G) \sim N\left(\mu, \frac{\sigma^2}{n}\right)$

Then using the standard formula for the variance of a log-normal distribution

$$var(G) = [\exp(\sigma^2/n) - 1]\exp(2\mu + \sigma^2/n)$$

The distribution of the median and its variance are not easily calculable. Laplace's asymptotic formula for the variance of a sample median (for large samples) is

$$\frac{1}{4(n+2)f(m)^2}$$

where n is the sample size, m is the population median and f is the PDF of the population distribution. For our log-normal case, we have $m = \exp(\mu)$ and

$$f(m) = \frac{\exp(-\mu)}{\sigma\sqrt{2\pi}}$$

Therefore

$$var(M) \cong \frac{\pi\sigma^2}{2(n+2)}\exp(2\mu)$$

The variance ratio for the two estimators is

$$\frac{var(G)}{var(M)} = \frac{2}{\pi}\frac{2+n}{n} g\left(\frac{\sigma^2}{n}\right)$$

where $g(\cdot)$ is the function

$$g(x) = \frac{1}{x}\exp(x)[\exp(x) - 1]$$

This is an increasing function with limit $g(x) \to 1$ as $x \to 0$. Therefore, for all sufficiently large sample sizes n, we have that

$$\frac{var(G)}{var(M)} \approx \frac{2}{\pi} < 1$$

and the geometric mean is the more efficient estimator. In the limiting case above, the sample geometric mean has a standard error that is about $\sqrt{2/\pi} \approx 80\%$ of that of the median.

For very small samples or sufficiently high population variance (at fixed sample size), the relative efficiency of the estimators can be reversed. If

$$\frac{\sigma^2}{n} > g^{-1}\left(\frac{\pi}{2}\right) \approx 0.3$$

this is sufficient for the median to become the more efficient estimator. However, for reasonable sample sizes, this requires *implausibly* wide distributions of the underlying prices. For example, if $n = 10$, then we need $\sigma > \sqrt{10 \times 0.3} \approx 1.7$. A 95% of the probability mass would lie with log prices within ± 2 standard deviations of μ. Therefore, the lowest and highest prices would vary by a factor of $\exp(4 \times 1.7) \approx 1000$. The median can, therefore, only be more efficient with extremely small samples (at which point the Laplace approximation is no longer valid anyway).

Although we are analytically approximating the variance of the sample median, these conclusions can also be shown numerically with Monte Carlo simulation, reported subsequently. This avoids concerns about analytical approximations that may be invalidated in small samples.

We conclude that, whilst the median may have desirable characteristics in terms of robustness to outliers, if the price data is log-normal, the geometric mean is more efficient (i.e. a lower variance estimate) than the median. This is because the median discards a large amount of information. However, the geometric mean is more sensitive to outliers, as we discuss below.

A.4 Hodges-Lehmann estimator

Fortunately, there are estimators are almost as efficient as the geometric mean under the hypothesis of a log-normal population, yet also reasonably robust to outliers. The Hodges-Lehmann estimator is a simple robust and non-parametric estimator of the population's location parameter μ.

If X_i are the observations, the Hodges-Lehmann estimator is defined as the median of pairwise averages

$$L = median\left\{\frac{X_i + X_j}{2} : i \leq j\right\}$$

Here the median is taken over $n(n+1)/2$ values.

A.5 Monte Carlo estimates of standard errors

The relative efficiency of the estimators is shown below, calculating by Monte Carlo using 10^6 trials. We can see that the HL estimator is almost as efficient as the geometric mean.

Table 13: Central estimator efficiency

	$n = 10$		$n = 20$	
	$\sigma = 0.1$	$\sigma = 1$	$\sigma = 0.1$	$\sigma = 1$
Geo mean	0.032	0.34	0.023	0.23
Median	0.037	0.41	0.027	0.29
HL	0.033	0.36	0.023	0.24

A.6 Robustness to outliers

The robustness of an estimator can be measure by its *breakdown point*. This is the proportion of observations that can moved *away* from distribution's centre to arbitrarily large values before the estimator is affected.

The geometric mean (like the arithmetic mean) has a breakdown point of 0, as changing any observation affects its value.

The median has a breakdown point of 50%. We could increase all the observations above the median without affecting its value.

The HL estimator has a breakdown point of $1-\frac{1}{\sqrt{2}} \approx 29\%$ for large n. To derive this, suppose that m of the n observations are contaminated. Then amongst the pairwise averages whose median is taken, $(n-m)(n-m+1)/2$ will be uncontaminated. To leave this median unchanged, we need at most half of the cases to be changed. Therefore, the maximum value of m is set by

$$\frac{(n-m)(n-m+1)}{2} \leq \frac{n(n-1)}{4}$$

or equivalently

$$\left(\frac{m}{n}\right)^2 - \frac{m}{n}\left(\frac{1}{n}+2\right) + \frac{1}{2}\left(1+\frac{3}{2n}\right) = 0$$

at the critical value of m. For large n this becomes

$$\left(\frac{m}{n}\right)^2 - 2\frac{m}{n} + \frac{1}{2} = 0$$

from which we take the root $\frac{m}{n} = 1 - \frac{1}{\sqrt{2}}$.

A.7 Sample size

We briefly consider what might be reasonable minimum sample sizes for benchmarking purposes. We suppose again that our price data is log-normally distributed, with the population of log prices having a $N(\mu, \sigma^2)$ distribution.

Draw a sample of size n from this population and calculate the sample mean $\bar{X}$ of the log prices. Then $\exp(\bar{X})$ is the geometric mean of the data, which again has a log-normal distribution. The expected value of sample mean of the log prices is $E(\bar{X}) = \mu$.

If the sample draws are uncorrelated (as would be implied if they are independent draws), then

$$var(\bar{X}) = \frac{\sigma^2}{n}$$

Suppose that we want to get a 95% confidence interval for prices expressed as a proportion m. Relative to a central estimate c, this interval is

$$[(1-m)c,\ (1+m)c]$$

For small m, $log(1+m) \cong m$. Therefore, in log prices, the confidence interval is approximately

$$[log(c) - m,\ log(c) + m]$$

For a $(1-p)$ confidence interval, we need (approximately) that

$$m = \frac{\alpha\,\sigma}{\sqrt{n}}$$

where $1 - \Phi(\alpha) = p/2$ and Φ of the CDF of a standard Normal distribution.

For a 95% confidence interval, $\alpha \approx 2$. A 68% confidence interval corresponds to $\alpha \approx 1$. For a 50% confidence interval, $\alpha \approx 0.67$.

Turning this around, the sample size we need to achieve a confidence interval m is

$$n \geq \frac{\alpha^2\sigma^2}{m^2}$$

m is then our target proportionate error. Notice that to halve the proportionate error m, we need *four times* as much data.

We can get an estimate of σ from our data (limiting to relevant cases only and after outlier rejection). From this, we can calculate sample size requirements to achieve a target error with a certain confidence. The table below shows the requirements for a 25% error target.

Table 14: Estimated σ and sample size requirements for each band group

Band group	**Actual sample size**	**σ estimate**	**$\alpha = 2$ (95% confidence)**	**$\alpha = 1$ (68% confidence)**	**$\alpha = 0.67$ (50% confidence)**
Sub-1 GHz	39	0.90	50	13	6
Lower 1-3 GHz	26	1.06	69	18	8
Upper 1-3 GHz	44	1.10	74	19	9

3.4-3.8 GHz	55	1.27	99	26	12

If we reduced the error target from 25% to 20% we would need roughly half as much data again (56% more observations). We take from this that around 15 is the practical lower limit for testing differences in any subsample.

In practice, our assumption that observations are uncorrelated is not likely to hold. This is because award occur in groups and there may be related factors driving prices of similar bands especially if in similar regions and occurring at similar times.

If observations are correlated, then the standard error becomes

$$var(\bar{X}) = \frac{\sigma^2}{n}(1 + (n-1)\rho)$$

where ρ is the average correlation across all pairs of observations. Therefore, the standard error becomes larger if $\rho > 0$, requiring a larger sample for the same target error. For a 95% confidence internal with proportionate error of at most m, it is sufficient that

$$n \geq (1 + \rho)\frac{\alpha^2\sigma^2}{m^2}$$

We can estimate the correlation between consecutive award prices within our sample (i.e. the serial autocorrelation). This varies across band groups, but is high as 12% for the full sample, increasing to 23% in the GDP cohort and 36% in the population density cohort. A worst case is that all pairs of observations were correlated to this degree (though this is unlikely as observations more distant in time may be less correlated). Nevertheless, as a rule of thumb, we could need around 25% more observations that the simple analysis above suggests due to positive correlations.

Annex B Use of cohort IQRs for validation

The ACMA validation procedure is essentially to:

- compute a central estimator for the whole sample; and
- find the IQR of a sub-set of data selected by a criterion such as GDP, population density or urbanisation.

The validation test is passed if the central estimate of the whole sample lies in the IQR of the subsample.

This approach is also used by the ACMA to select between possible alternative central estimators (median and geometric mean) applied to the whole sample. However, we focus on the role of the IQR as a validation test for a single estimator in the analysis that follows.

This validation process can be thought of as an implicit statistical test of the subset having a different central estimate. However, it is not apparent what confidence standard is being applied, as this is highly dependent on what proportion of the whole sample falls into the subsample. Under the null hypothesis that the subsample is drawn from the same population as the other data in the full sample:

- If the subsample is a large proportion of the sample, the chance of failing the validation test (i.e. a Type-I error) is small (potentially negligible);
- Where the subsample is a small proportion of the sample, there may be a high probability of failing the validation test due to uncertainty about the IQR. The validation test would have low statistical significance in the conventional sense, as it is often failed at random.

We can investigate quantitatively. Take a sample of size N draw from a lognormal distribution. From this, draw a subsample of size fN, where f is the fraction taken.

Using Monte Carlo simulation (with 10,000 draws of the sample), we calculate the probability that the GHL estimator for the whole sample lies *outside* the IQR of the subsample for various sample and subsample sizes. This is a Type-I error.

Table 15: Type-I error probabilities

$\sigma = 1$	$f = 5\%$	$f = 10\%$	$f = 20\%$	$f = 33\%$	$f = 50\%$	$f = 80\%$
$N = 30$	0.490	0.323	0.181	**0.062**	0.010	0.
$N = 50$	0.324	0.190	**0.081**	0.012	0.001	0.
$N = 100$	0.204	**0.094**	0.011	0.001	0.	0.
$N = 150$	0.119	0.034	0.002	0.	0.	0.
$N = 200$	**0.103**	0.014	0.	0.	0.	0.

Red shading if >5% *Bold where the subsample size is 10*

Note that the choice of the mean and variance of the underlying distribution does not affect Type-I error probabilities above. The mean is a location parameter which is irrelevant as we are only considering the difference between the IQR and the GHL estimate and the variance scales both the distribution of the GHL estimator and the IQR of the subsample in the same way.

We can see from the table that, as a rough rule of thumb, failure of the validation test does not provide significant evidence of structural difference of the subsample if the subsample is much smaller than 15 (though the overall sample size also matters). As the subsample becomes a large enough proportion of the sample, it becomes very unlikely that the validation test is failed at random (i.e. the probability of Type-I error), so any failure becomes highly significant. Therefore, the problem with the validation test is its small sample performance.

The difficulty with interpreting the validation test is that we are not computing a metric for how different the subsample is from the overall sample, that can then be used to calculate a p-value measuring how significant any difference is. Rather, we are using a binary pass/fail test with a variable level of statistical significance depending primarily on how large the subsample is relative to the sample (but also the overall sample sizes).

Type-II errors occur if the subsample is different to the overall sample, but the validation test is passed. There are two potential ways this can occur:

- Where the subsample is small, the IQR is poorly determined and the central estimator for the whole sample could fall into the IQR at random;
- Where the subsample is a large fraction of the main sample and we use a robust estimator (such as GHL) on the whole sample, the central estimate may be relatively unaffected by the observations *outside* of the subsample and so fall into the subsample IQR anyway.

The validation test performs better in regard to Type-II errors provided that the subsample is not very small. To test this, we suppose that the subsample is draw from a lognormal distribution with mean μ and variance 1, with the remaining sample having mean 0 and variance 1.

If we set $\mu = 1.65$, this difference in the subsample mean from the whole sample mean would be at the boundary of statistical significant if we ran a t-test on the log prices at a significance level of 10%. Similarly, with a larger difference of $\mu = 1.96$, the difference would be at the boundary of significance at 5%.

Table 16: Type-II error probabilities (Subsample different significance at 10%)

$\Delta\mu = 1.65$	$f = 5\%$	$f = 10\%$	$f = 20\%$	$f = 33\%$	$f = 50\%$	$f = 80\%$
$N = 30$	0.104	0.089	0.071	**0.065**	0.069	0.127
$N = 50$	0.086	0.054	**0.036**	0.024	0.029	0.077
$N = 100$	0.048	**0.024**	0.006	0.004	0.006	0.024
$N = 150$	0.021	0.008	0.001	0.001	0.001	0.011
$N = 200$	**0.013**	0.002	0.	0.	0.	0.003

Red shading if >5% *Bold where the subsample size is 10*

Table 17: Type-II error probabilities (Subsample difference significant at 5%)

$\Delta\mu = 1.96$	$f = 5\%$	$f = 10\%$	$f = 20\%$	$f = 33\%$	$f = 50\%$	$f = 80\%$
$N = 30$	0.055	0.04	0.023	**0.018**	0.013	0.031
$N = 50$	0.035	0.018	**0.008**	0.003	0.004	0.007
$N = 100$	0.012	**0.004**	0.	0.	0.	0.001
$N = 150$	0.003	0.	0.	0.	0.	0.
$N = 200$	**0.002**	0.	0.	0.	0.	0.

Red shading if >5% *Bold where the subsample size is 10*

We conclude that at typical overall sample sizes for benchmark data (around 150 observations) and typical subset sizes (20-30% of the main sample), the validation procedure works reasonably well and has a low probability of Type-I and Type-II errors. Interpreted as an implicit statistical test, with these sample and subsample sizes if evidence of a different central estimate for the subsample would need to be significant at the 1-2% level for the validation test to be failed. Therefore, it is reasonable to describe this as a validation test for these sample sizes given the heightened standard of evidence required to fail the test.

However, as sample sizes become smaller and if a smaller proportion of the whole sample is taken as a subsample, Type-I errors rapidly grow, due to the uncertainty around an IQR calculated from few observations. As rules of thumb:

- With 10 or fewer observations in the subsample, the probability of Type-I errors becomes high enough that the validation test will be failed sufficiently often that the test is no longer useful;
- Extreme caution should be taken if the subsample is a small (<20%) proportion of the main sample, as then the main sample needs to be sufficiently large otherwise there may be a severe risk of Type-I errors. For example, if the subsample is only 10% of the main sample, we need more than 200 observations in the main sample to control the risk of Type-I errors to around 10%.

Annex C Award exclusion

In this annex, we provide further detail on the criteria that we have used to exclude certain awards from the sample.

Table 18: Criteria for exclusion

Exclusion category	**Criteria**	**Description**	**Practical exclusion rules**[36]
Uncompetitive award	Uncompetitive format	Prices of **administrative awards** do not provide genuine market information except potentially a soft lower bound of valuation.	Format is not a competitive auction.
	Limited participation	Infeasible for prices to increase above reserve given the number of bidders participating and/or binding caps.	Maximum amount of spectrum/number of licences that could be won is less than or equal to total amount on offer. For example: • only one bidder; or • three bidders bidding for three similar/identical licences, cap of one licence per bidder.
	Material amounts of spectrum unsold	Awards that are **not competitive** but could have been under the same format/auction rules with lower reserve prices or different licence conditions. It is not necessary to exclude all awards with unsold spectrum (e.g. if spectrum only went unsold in unattractive regions or encumbered lot categories).	Amount of bandwidth sold is materially less than bandwidth offered, or when final prices are set by reserve prices. Unsold spectrum only in encumbered categories would *not* be passed as material.

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[36] Where possible, we have provided a clear exclusion rule; however, for some criteria, it is harder to draw a definitive line (e.g. *special* obligations). We face a trade-off between comparability and ensuring a good sample size for our analysis, therefore there may be cases these rules are not authoritative. Full explanations of each excluded award are detailed below.

Licences not comparable	Special obligations	Prices of awards that incorporate **onerous rollout obligations** or **investment commitments** do not reflect full market valuation. Obligations for excluded awards should be explicitly interventionist (not precautionary use-it-or-lose-it conditions).	Separate lot categories with additional obligations – if possible, exclude only these lots, not the entire award. Investment commitments in lieu of licence fees.
	Use case restricted	The licences on offer are **not comparable** as they *could not* be held by the operators holding existing licences in Australia.	Neither of the following applies to the licence: • it is service/technology neutral; nor • it can be used to operate a mobile network.
	Residual awards	Awards of lots that were undesirable in the main award, typically offering **materially limited bandwidths or short-term licences**, are recommended to be excluded.	Duration of less than ten years, generally to line expiration up with other assigned licences. Licences only available in a small number of regions covering a minority of the country's population. Bandwidth available materially less than that of the bandwidth offered in the previous award.
Measurement issues	Lack of information	Sufficient information to calculate award prices is **unavailable.** Includes cases where available data is clearly **incorrect** if correction is not possible.	Prices, bandwidths, durations or population numbers are not public. Unable to calculate **per band** prices (e.g. in combinatorial awards). **Annual fees are known to be high** enough to affect operators' valuation, but there is **not sufficient public information** of annual fees.

There are some other potential conditions based on which we have concerns on including certain awards. These conditions typically reduce spectrum value. As they are difficult to apply in a clear-cut manner, we have not applied these as award exclusion criteria. They include:

- Country not comparable:

  Countries with different development level, telecommunication infrastructure, regulatory frameworks, foreign investment situation and financing concerns may have a very different market for spectrum auctions. However, it is difficult to draw the definitive line of comparability. Therefore, comparability of a country is not used as a basis to exclude awards in our analysis. This concern is also mitigated by cohort analysis.

- Resulting prices marginally above reserve price:

  Competition concerns arise when resulting prices are only marginally above reserve price. These prices may not be the result of competition from excess demand. Instead, they can be driven by the auction mechanism. The bidders may be shifting bids across substitutable lots in each round with the prices increasing at the same time, but the auction was merely solving an allocation problem. The final price being higher than reserve price in this case would be the product of auction format rather than excess demand. While a concern, this is also difficult to implement in practice. Therefore, awards are only excluded when there is a clear sign of being uncompetitive, such as limited participation and material amounts of spectrum unsold.

Below is the table of awards which have been suggested by stakeholders to include, or had previously been included in the sample, and we have chosen to exclude from our analysis.

Table 19: Excluded awards

Country	**Year**	**Frequency Band(s)**	**Reason for exclusion**
Austria	2024	3500 MHz	Licences not comparable: residual award for regional licences.
Brazil	2010	2100 MHz	Uncompetitive award: only 60 MHz out of 165 MHz was sold.

	2014	700 MHz	Licence not comparable: extra payment to TV operators for vacating the spectrum.
	2021	700 MHz, 2300 MHz & 3500 MHz	Licences not comparable: most of the bid value was assigned to 'investment commitments' rather than paid to the government.
Bulgaria	2021	2600 MHz	Uncompetitive award: administrative allocation.
Colombia	2023	2600 MHz	Uncompetitive award: only 10 MHz out of 30 MHz was sold.
	2023	3500 MHz	Lack of information: upfront fee cannot be calculated due to insufficient information regarding deferred payments.
Croatia	2013	800 MHz	Uncompetitive award and licences not comparable: residual award where two operators won 2x10 MHz each with a third block of 2x10 MHz remaining unassigned.
	2015	1800 MHz	Uncompetitive award: spectrum cap binding for all but one MNO therefore only one bidder.
	2023	3500 MHz	Uncompetitive award: residual spectrum from a 2021 auction was re-auctioned at a regional level. Material amount of spectrum went unsold.
Denmark	2021	1400 MHz	Lack of information: combinatorial auction therefore unable to determine price per band.
Estonia	2017	2.6 GHz	Lack of information.
Georgia	2024	700 MHz, 800 MHz, 2600 MHz & 3500 MHz	Uncompetitive award: only one bidder.
Hungary	2016	3500 MHz	Uncompetitive award: only 60 MHz out of 160 MHz of FDD spectrum sold and only 20 MHz out of 200 MHz of TDD spectrum sold in the band.
Iceland	2017	2100 MHz & 2600 MHz	Licences not comparable: 2100 MHz licences were residual from previous auction and only had a five-year duration. 2600 MHz licences were dependent on achieving certain coverage in one year and one of the winners had their licence revoked due to not meeting these obligations.
Latvia	2017	3500 MHz	Uncompetitive award: only one bidder.
Mexico	2010	1800 MHz	Lack of information.
	2018	2600 MHz	Licences not comparable: spectrum purchased in the auction was returned the following year due to onerous coverage obligations.
	2021	800 MHz & 2600 MHz	Licences not comparable and uncompetitive award: only 3 lots sold out of 41 offered. Operators blamed high prices and special obligations.

Moldova	2025	700 MHz, 850 MHz, 1.5 GHz & 3.6 GHz	Uncompetitive award: material amounts of spectrum unsold in every band in this award.
Peru	2025	3500 MHz	Uncompetitive award: licences were not allocated through an auction. Instead, bidders made 'investment commitments' and were not required to pay the regulator.
Portugal	2021	900 MHz	Uncompetitive award: all sold at reserve and material amount reserved for entrant.
Romania	2015	3500 MHz	Uncompetitive award: 7 of the unpaired blocks and 5 of the paired blocks went unsold. Additionally, regulator made changes to auction rules that favoured incumbents and resulted in prices close to reserve.
	2021	800 MHz, 2600MHz & 3500 MHz	Licences not comparable: licences were residual awards of short-term licences co-terminating with other licences in these bands.
Singapore	2017	900 MHz	Uncompetitive award: majority of this spectrum was awarded administratively.
South Africa	2022	700 MHz, 800 MHz, 2600 MHz & 3500 MHz	Lack of information: only package prices reported.
Spain	2011	1800 MHz	Uncompetitive award and licences not comparable: beauty contest with one bidder and investment commitments.
Sweden	2016	1800 MHz	Uncompetitive award: only one bidder.
Thailand	2018	1800 MHz	Uncompetitive award: only 20 MHz out of 90 MHz sold.
	2025	1500 MHz	Uncompetitive award: only 20 MHz sold out of 55 MHz offered.
Uruguay	2017	1700 MHz & 2200 MHz	Uncompetitive award: only 20 MHz out of 50 MHz sold.
Vietnam	2024	3500 MHz	Uncompetitive award: spectrum from the auction earlier in the year unsold due to the lack of qualified bidder. Spectrum was sold in this auction at reserve price, which does not qualify as competitive award.

Annex D Data sensitivity

D.1 Price sensitivity to included awards

In Section 6 we presented the awards for each band group that would have the largest effect on the GHL price if excluded just that award in from the benchmarking sample. This helps assess claims that prices are being driven upwards by the inclusion of outliers. In the table below, we list all awards, in descending order of the absolute value of their effect on the GHL price, by band group. We also include the equivalent statistics for the price as calculated under Step 6, the median and the geometric mean. Negative values indicate that the price would decrease on removing an award, positive values that it would increase.

Table 20: Changes to the single price estimates as a result of removing observations

Band group	Observation	Step 6 price	Median	Geom. mean	GHL
Sub-1 GHz	Estonia - 700 MHz - 2022	4.3%	0.6%	4.3%	4.1%
Sub-1 GHz	Vietnam - 700 MHz - 2025	3.7%	0.6%	3.7%	4.0%
Sub-1 GHz	Austria - 700 MHz (FDD) - 2020	3.5%	0.6%	3.5%	4.0%
Sub-1 GHz	Hong Kong - 850 MHz - 2021	3.3%	0.6%	3.3%	4.0%
Sub-1 GHz	Latvia - 700 MHz (FDD) - 2021	3.0%	0.6%	3.0%	4.0%
Sub-1 GHz	Thailand - 700 MHz - 2020	-4.0%	-0.6%	-4.0%	-4.0%
Sub-1 GHz	Hong Kong - 700 MHz - 2021	2.8%	0.6%	2.8%	4.0%
Sub-1 GHz	Hong Kong - 900 MHz - 2018	-3.3%	-0.6%	-3.3%	-3.6%
Sub-1 GHz	Canada - 600 MHz - 2019	-2.9%	-0.6%	-2.9%	-3.5%
Sub-1 GHz	Hungary - 700 MHz (FDD) - 2020	-2.7%	-0.6%	-2.7%	-3.5%
Sub-1 GHz	Hungary - 900 MHz - 2021	-2.3%	-0.6%	-2.3%	-3.4%
Sub-1 GHz	Australia - 850 MHz & 900 MHz - 2021	-1.8%	-0.6%	-1.8%	-3.4%
Sub-1 GHz	Sweden - 700 MHz - 2018	-1.7%	-0.6%	-1.7%	-3.4%
Sub-1 GHz	Croatia - 700 MHz - 2021	1.5%	0.6%	1.5%	3.2%
Sub-1 GHz	Moldova - 700 MHz - 2025	1.5%	0.6%	1.5%	3.2%
Sub-1 GHz	Sweden - 900 MHz - 2023	1.3%	0.6%	1.3%	3.0%
Sub-1 GHz	United Kingdom - 700 MHz - 2021	1.1%	0.6%	1.1%	3.0%
Sub-1 GHz	Chile - 700 MHz (FDD) - 2021	1.1%	0.6%	1.1%	2.6%
Sub-1 GHz	Switzerland - 700 MHz (FDD) - 2019	1.0%	0.6%	1.0%	2.5%

Sub-1 GHz	Norway - 700 MHz (FDD) - 2019	0.9%	0.6%	0.9%	2.5%
Sub-1 GHz	Italy - 700 MHz - 2018	-1.4%	-0.6%	-1.4%	-2.1%
Sub-1 GHz	Czechia - 700 MHz - 2020	-1.3%	-0.6%	-1.3%	-2.1%
Sub-1 GHz	Slovakia - 700 MHz - 2020	-1.2%	-0.6%	-1.2%	-1.9%
Sub-1 GHz	Luxembourg - 700 MHz - 2020	-0.9%	-0.6%	-0.9%	-0.9%
Sub-1 GHz	Netherlands - 700 MHz (FDD) - 2020	-0.9%	-0.6%	-0.9%	-0.9%
Sub-1 GHz	Romania - 800 MHz - 2021	-0.8%	-0.6%	-0.8%	-0.9%
Sub-1 GHz	Croatia - 800 MHz & 900 MHz - 2023	-0.8%	-0.6%	-0.8%	-0.9%
Sub-1 GHz	Spain - 700 MHz - 2021	-0.8%	-0.6%	-0.8%	-0.9%
Sub-1 GHz	Portugal - 700 MHz - 2021	-0.5%	-0.6%	-0.5%	-0.9%
Sub-1 GHz	Greece - 700 MHz - 2020	-0.4%	-0.6%	-0.4%	-0.9%
Sub-1 GHz	Slovenia - 700 MHz - 2021	-0.4%	0.0%	-0.4%	-0.9%
Sub-1 GHz	Belgium - 700 MHz & 900 MHz - 2022	-0.3%	0.6%	-0.3%	-0.9%
Sub-1 GHz	Lithuania - 700 MHz - 2022	-0.3%	0.6%	-0.3%	-0.7%
Sub-1 GHz	Poland - 700 MHz & 800 MHz - 2025	-0.1%	0.6%	-0.1%	-0.7%
Sub-1 GHz	Hong Kong - 850 MHz & 900 MHz - 2024	0.2%	0.6%	0.2%	-0.2%
Lower 1-3 GHz	Latvia - 1400 MHz - 2022	12.9%	3.0%	12.9%	14.7%
Lower 1-3 GHz	Slovenia - 1.5 GHz - 2021	8.6%	3.0%	8.6%	14.7%
Lower 1-3 GHz	Sweden - 2.1 GHz - 2023	6.9%	3.0%	6.9%	14.7%
Lower 1-3 GHz	Austria - 1500 MHz - 2020	45.8%	3.0%	5.2%	14.3%
Lower 1-3 GHz	Moldova - 1.5 GHz - 2025	6.2%	3.0%	6.2%	14.3%
Lower 1-3 GHz	Chile - AWS - 2021	5.6%	3.0%	5.6%	14.3%
Lower 1-3 GHz	Sweden - 1800 MHz - 2025	2.7%	3.0%	2.7%	13.2%
Lower 1-3 GHz	Hong Kong - 1800 MHz - 2018	-8.3%	-10.1%	-8.3%	-6.9%
Lower 1-3 GHz	Slovenia - 2.1 GHz - 2021	-5.1%	-10.1%	-5.1%	-4.3%
Lower 1-3 GHz	Hungary - 1800 MHz - 2021	-4.6%	-10.1%	-4.6%	-4.3%
Lower 1-3 GHz	Portugal - 1800 MHz & 2.1 GHz - 2021	-4.2%	-10.1%	-4.2%	-4.3%
Lower 1-3 GHz	Croatia - 1800 MHz & 2.1 GHz - 2023	-4.1%	-10.1%	-4.1%	-4.3%
Lower 1-3 GHz	Singapore - 2100 MHz (FDD) - 2021	-3.3%	-10.1%	-3.3%	-4.3%
Lower 1-3 GHz	Netherlands - 1400 MHz & 2100 MHz - 2020	-3.0%	-10.1%	-3.0%	-4.3%
Lower 1-3 GHz	Hungary - 2.1 GHz - 2020	-3.0%	-10.1%	-3.0%	-4.1%
Lower 1-3 GHz	Germany - 2.1 GHz - 2019	-2.8%	-10.1%	-2.8%	-4.1%
Lower 1-3 GHz	Uruguay - 1.7-2.2 GHz - 2019	-2.2%	-10.1%	-2.2%	-4.1%
Lower 1-3 GHz	Belgium - 1400 MHz - 2022	-1.8%	-10.1%	-1.8%	-4.1%
Lower 1-3 GHz	Belgium - 1800 MHz & 2.1 GHz - 2022	-1.6%	-7.1%	-1.6%	-4.1%

Lower 1-3 GHz	Norway - 2100 MHz (FDD) - 2019	-0.6%	3.0%	-0.6%	-3.3%
Lower 1-3 GHz	Austria - 2100 MHz (FDD) - 2020	-0.4%	3.0%	-0.4%	-3.3%
Lower 1-3 GHz	Switzerland - 1400 MHz - 2019	-0.3%	3.0%	-0.3%	-0.9%
Lower 1-3 GHz	Greece - 2 GHz - 2020	0.1%	3.0%	0.1%	-0.2%
Upper 1-3 GHz	Hong Kong - 2.3 GHz - 2024	-2.8%	-2.8%	-4.3%	-4.7%
Upper 1-3 GHz	Singapore - 2.5 GHz - 2017	-2.8%	-2.8%	-4.9%	-4.7%
Upper 1-3 GHz	South Korea - 2600 MHz - 2016	-2.8%	-2.8%	-5.7%	-4.7%
Upper 1-3 GHz	Canada - 2.6 GHz - 2015	-6.2%	-2.8%	-2.7%	-3.8%
Upper 1-3 GHz	Portugal - 2.6 GHz - 2021	-2.8%	-2.8%	-3.0%	-3.8%
Upper 1-3 GHz	Singapore - 2.5 GHz - 2013	-2.8%	-2.8%	-3.0%	-3.8%
Upper 1-3 GHz	Uruguay - 2.6 GHz - 2019	-6.1%	-2.8%	-2.6%	-3.7%
Upper 1-3 GHz	Hong Kong - 2600 MHz (FDD) - 2021	-2.8%	-2.8%	-2.6%	-3.7%
Upper 1-3 GHz	Turkiye - 2600 MHz - 2015	-2.8%	-2.8%	-2.5%	-3.7%
Upper 1-3 GHz	Finland - 2.6 GHz - 2009	4.8%	2.8%	8.7%	3.6%
Upper 1-3 GHz	Lithuania - 2.6 GHz - 2012	2.8%	2.8%	5.9%	3.6%
Upper 1-3 GHz	Nigeria - 2.3 GHz - 2014	2.8%	2.8%	6.3%	3.6%
Upper 1-3 GHz	Romania - 2.6 GHz - 2021	-2.8%	-2.8%	-2.3%	-3.6%
Upper 1-3 GHz	Czechia - 2.6 GHz - 2016	-2.8%	-2.8%	-1.7%	-3.4%
Upper 1-3 GHz	Hong Kong - 2.3 GHz - 2012	-2.8%	-2.8%	-1.9%	-3.4%
Upper 1-3 GHz	Thailand - 2.6 GHz - 2020	-2.8%	-2.8%	-1.7%	-3.4%
Upper 1-3 GHz	United States - 2.5 GHz - 2022	2.8%	2.8%	4.2%	3.3%
Upper 1-3 GHz	Australia - 2.5 GHz - 2013	2.8%	2.8%	3.8%	3.3%
Upper 1-3 GHz	Austria - 2.6 GHz - 2010	2.8%	2.8%	2.5%	3.3%
Upper 1-3 GHz	Germany - 2.6 GHz - 2010	2.8%	2.8%	2.6%	3.3%
Upper 1-3 GHz	France - 2.6 GHz - 2011	-2.8%	-2.8%	-1.2%	-3.2%
Upper 1-3 GHz	Slovenia - 2.3 GHz - 2021	-2.8%	-2.8%	-1.3%	-3.2%
Upper 1-3 GHz	Spain - 2.6 GHz - 2011	2.8%	2.8%	2.1%	2.8%
Upper 1-3 GHz	Sweden - 2.3 GHz - 2021	2.8%	2.8%	1.9%	2.3%
Upper 1-3 GHz	Italy - 2.6 GHz (TDD) - 2011	2.8%	2.8%	0.9%	2.1%
Upper 1-3 GHz	Sweden - 2.6 GHz - 2023	2.8%	2.8%	1.1%	2.1%
Upper 1-3 GHz	Greece - 2.6 GHz - 2014	2.8%	2.8%	0.8%	1.5%
Upper 1-3 GHz	Norway - 2.6 GHz - 2021	-3.0%	2.8%	0.6%	1.1%
Upper 1-3 GHz	Belgium - 2.6 GHz - 2011	2.8%	2.8%	0.7%	1.1%
Upper 1-3 GHz	Croatia - 2.6 GHz - 2023	2.8%	2.8%	0.4%	1.1%
Upper 1-3 GHz	Czechia - 2.6 GHz - 2013	2.8%	2.8%	0.7%	1.1%
Upper 1-3 GHz	Poland - 2.6 GHz - 2015	2.8%	2.8%	0.5%	1.1%
Upper 1-3 GHz	Italy - 2.6 GHz (FDD) - 2011	-2.8%	-2.8%	-0.2%	0.6%
Upper 1-3 GHz	Spain - 2600 MHz (FDD) - 2016	-2.8%	-2.8%	-0.2%	0.6%
Upper 1-3 GHz	Vietnam - 2.6 GHz - 2024	2.8%	2.8%	-0.0%	0.6%
Upper 1-3 GHz	United Kingdom - 2.3 GHz - 2018	-2.8%	-2.8%	-0.5%	-0.3%

3.4-3.8 GHz	Latvia - 3.5 GHz - 2023	13.8%	2.8%	5.5%	3.9%
3.4-3.8 GHz	Bulgaria - 3.6 GHz - 2021	5.7%	2.8%	5.7%	3.9%
3.4-3.8 GHz	Spain - 3500 MHz - 2016	3.8%	2.8%	3.8%	3.7%
3.4-3.8 GHz	Lithuania - 3.5 GHz - 2022	3.1%	2.8%	3.1%	3.7%
3.4-3.8 GHz	Canada - 3.5 GHz - 2021	-6.2%	-3.9%	-6.2%	-3.5%
3.4-3.8 GHz	Switzerland - 3500 MHz (5G) - 2019	2.5%	2.8%	2.5%	3.3%
3.4-3.8 GHz	Netherlands - 3500 MHz (5G) - 2024	2.2%	2.8%	2.2%	3.3%
3.4-3.8 GHz	Estonia - 3500 MHz (5G) - 2022	2.0%	2.8%	2.0%	3.1%
3.4-3.8 GHz	Nigeria - 3.5 GHz - 2021	1.9%	2.8%	1.9%	3.1%
3.4-3.8 GHz	Greece - 3.6 GHz - 2020	1.8%	2.8%	1.8%	3.1%
3.4-3.8 GHz	Slovakia - 3.5 GHz - 2022	1.8%	2.8%	1.8%	3.1%
3.4-3.8 GHz	Czechia - 3700 MHz - 2017	1.7%	2.8%	1.7%	3.1%
3.4-3.8 GHz	United States - 3.7 GHz - 2021	-4.6%	-3.9%	-4.6%	-3.0%
3.4-3.8 GHz	United States - 3.45 GHz - 2021	-4.1%	-3.9%	-4.1%	-3.0%
3.4-3.8 GHz	Portugal - 3.6 GHz - 2021	-3.7%	-3.9%	-3.7%	-3.0%
3.4-3.8 GHz	Italy - 3.7 GHz - 2018	-3.0%	-3.9%	-3.0%	-2.9%
3.4-3.8 GHz	Finland - 3.5 GHz - 2018	1.6%	2.8%	1.6%	2.9%
3.4-3.8 GHz	South Korea - 3.5 GHz - 2018	-2.5%	-3.9%	-2.5%	-2.8%
3.4-3.8 GHz	Sweden - 3.5 GHz - 2021	1.4%	2.8%	1.4%	2.8%
3.4-3.8 GHz	Poland - 3.6 GHz - 2023	1.4%	2.8%	1.4%	2.8%
3.4-3.8 GHz	United States - 3500 MHz (5G) - 2020	-2.0%	-3.9%	-2.0%	-2.7%
3.4-3.8 GHz	Australia - 3.6 GHz - 2018	-1.9%	-3.9%	-1.9%	-2.7%
3.4-3.8 GHz	Ireland - 3500 MHz (5G) - 2017	1.3%	2.8%	1.3%	2.5%
3.4-3.8 GHz	Croatia - 3.6 GHz - 2021	1.2%	2.8%	1.2%	2.5%
3.4-3.8 GHz	Germany - 3.6 GHz - 2019	-1.6%	-3.9%	-1.6%	-2.4%
3.4-3.8 GHz	France - 3.6 GHz - 2020	-1.4%	-3.9%	-1.4%	-1.9%
3.4-3.8 GHz	Belgium - 3.5 GHz - 2022	1.0%	2.8%	1.0%	1.8%
3.4-3.8 GHz	Australia - 3.4 GHz - 2023	0.9%	2.8%	0.9%	1.7%
3.4-3.8 GHz	Moldova - 3.6 GHz - 2025	0.9%	2.8%	0.9%	1.7%
3.4-3.8 GHz	Austria - 3.5 GHz - 2019	0.8%	2.8%	0.8%	1.5%
3.4-3.8 GHz	Latvia - 3500 MHz (5G) - 2018	-1.3%	-3.9%	-1.3%	-1.3%
3.4-3.8 GHz	Colombia - 3.5 GHz - 2023	-1.2%	-3.9%	-1.2%	-1.3%
3.4-3.8 GHz	Hungary - 3500 MHz (5G) - 2020	-1.2%	-3.9%	-1.2%	-1.3%
3.4-3.8 GHz	Canada - 3.8 GHz - 2023	-1.0%	-3.9%	-1.0%	-0.7%
3.4-3.8 GHz	United Kingdom - 3.4 GHz - 2018	-0.9%	-3.9%	-0.9%	-0.6%
3.4-3.8 GHz	Australia - 3.7 GHz - 2023	-0.9%	-3.9%	-0.9%	-0.6%
3.4-3.8 GHz	Chile - 3500 MHz (5G) - 2021	-0.8%	-3.9%	-0.8%	-0.6%
3.4-3.8 GHz	Luxembourg - 3.6 GHz - 2020	-0.7%	-3.9%	-0.7%	-0.4%
3.4-3.8 GHz	Spain - 3.7 GHz - 2018	-0.6%	-3.9%	-0.6%	-0.4%

3.4-3.8 GHz	United Kingdom - 3.6 GHz - 2021	0.5%	2.8%	0.5%	0.3%
3.4-3.8 GHz	Norway - 3.6 GHz - 2021	-0.6%	-3.9%	-0.6%	-0.3%
3.4-3.8 GHz	Uruguay - 3.5 GHz - 2023	-0.4%	-3.9%	-0.4%	-0.3%
3.4-3.8 GHz	Singapore - 3500 MHz (5G) - 2020	-0.4%	-3.9%	-0.4%	-0.3%
3.4-3.8 GHz	Argentina - 3.5 GHz - 2023	-0.3%	-3.9%	-0.3%	-0.2%
3.4-3.8 GHz	Hong Kong - 3500 MHz (5G) - 2019	-0.2%	-1.1%	-0.2%	-0.2%
3.4-3.8 GHz	Slovenia - 3.6 GHz - 2021	-0.0%	2.8%	-0.0%	-0.2%
3.4-3.8 GHz	Czechia - 3500 MHz (5G) - 2020	0.2%	2.8%	0.2%	-0.0%

Awards of spectrum in a band group are our units of observation and the natural thing to think of removing from the sample. However, we can also look at the effect of removing all awards from a given country at the same time. Naturally, the size of the effect is linked to the number of awards in the country included in our sample. Below we present the equivalent table based on removing all awards in a given country at the same time, including the number of awards removed.

We note that many of the largest effects relate to awards of SDL spectrum, the price of which is significantly different to that of the 1800 and 2100 MHz bands, as shown in our previous report. Differences in the price distributions are visible in the density plot below.

Figure 7: Price density for SDL and other Lower 1-3 GHz awards

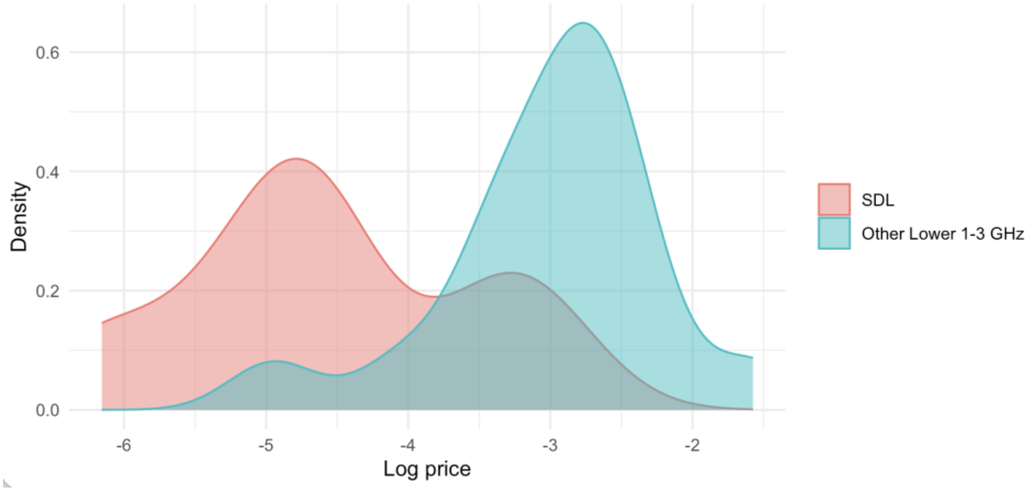


Table 21: Changes to single price estimates as a result of removing countries

Band group	Country	Awards	Step 6 price	Median	Geom. mean	GHL
Sub-1 GHz	Hong Kong	4	3.3%	1.3%	3.3%	5.3%
Sub-1 GHz	Hungary	2	-5.0%	-1.2%	-5.0%	-4.6%
Sub-1 GHz	Estonia	1	4.3%	0.6%	4.3%	4.1%
Sub-1 GHz	Vietnam	1	3.7%	0.6%	3.7%	4.0%
Sub-1 GHz	Austria	1	3.5%	0.6%	3.5%	4.0%
Sub-1 GHz	Latvia	1	3.0%	0.6%	3.0%	4.0%
Sub-1 GHz	Thailand	1	-4.0%	-0.6%	-4.0%	-4.0%
Sub-1 GHz	Canada	1	-2.9%	-0.6%	-2.9%	-3.5%
Sub-1 GHz	Australia	1	-1.8%	-0.6%	-1.8%	-3.4%
Sub-1 GHz	Moldova	1	1.5%	0.6%	1.5%	3.2%
Sub-1 GHz	United Kingdom	1	1.1%	0.6%	1.1%	3.0%
Sub-1 GHz	Chile	1	1.1%	0.6%	1.1%	2.6%
Sub-1 GHz	Switzerland	1	1.0%	0.6%	1.0%	2.5%
Sub-1 GHz	Norway	1	0.9%	0.6%	0.9%	2.5%
Sub-1 GHz	Italy	1	-1.4%	-0.6%	-1.4%	-2.1%
Sub-1 GHz	Czechia	1	-1.3%	-0.6%	-1.3%	-2.1%
Sub-1 GHz	Croatia	2	0.7%	0.0%	0.7%	1.9%
Sub-1 GHz	Slovakia	1	-1.2%	-0.6%	-1.2%	-1.9%
Sub-1 GHz	Luxembourg	1	-0.9%	-0.6%	-0.9%	-0.9%
Sub-1 GHz	Netherlands	1	-0.9%	-0.6%	-0.9%	-0.9%
Sub-1 GHz	Romania	1	-0.8%	-0.6%	-0.8%	-0.9%
Sub-1 GHz	Spain	1	-0.8%	-0.6%	-0.8%	-0.9%
Sub-1 GHz	Portugal	1	-0.5%	-0.6%	-0.5%	-0.9%
Sub-1 GHz	Greece	1	-0.4%	-0.6%	-0.4%	-0.9%
Sub-1 GHz	Slovenia	1	-0.4%	0.0%	-0.4%	-0.9%
Sub-1 GHz	Belgium	1	-0.3%	0.6%	-0.3%	-0.9%
Sub-1 GHz	Lithuania	1	-0.3%	0.6%	-0.3%	-0.7%
Sub-1 GHz	Poland	1	-0.1%	0.6%	-0.1%	-0.7%
Sub-1 GHz	Sweden	2	-0.5%	0.0%	-0.5%	-0.2%
Lower 1-3 GHz	Sweden	2	10.2%	6.0%	10.2%	23.5%
Lower 1-3 GHz	Latvia	1	12.9%	3.0%	12.9%	14.7%
Lower 1-3 GHz	Austria	2	50.1%	6.0%	4.9%	14.3%
Lower 1-3 GHz	Moldova	1	6.2%	3.0%	6.2%	14.3%
Lower 1-3 GHz	Chile	1	5.6%	3.0%	5.6%	14.3%
Lower 1-3 GHz	Slovenia	2	3.2%	0.0%	3.2%	9.7%
Lower 1-3 GHz	Hong Kong	1	-8.3%	-10.1%	-8.3%	-6.9%
Lower 1-3 GHz	Hungary	2	-7.8%	-20.2%	-7.8%	-6.9%
Lower 1-3 GHz	Belgium	2	-3.5%	-20.2%	-3.5%	-5.6%
Lower 1-3 GHz	Portugal	1	-4.2%	-10.1%	-4.2%	-4.3%
Lower 1-3 GHz	Croatia	1	-4.1%	-10.1%	-4.1%	-4.3%

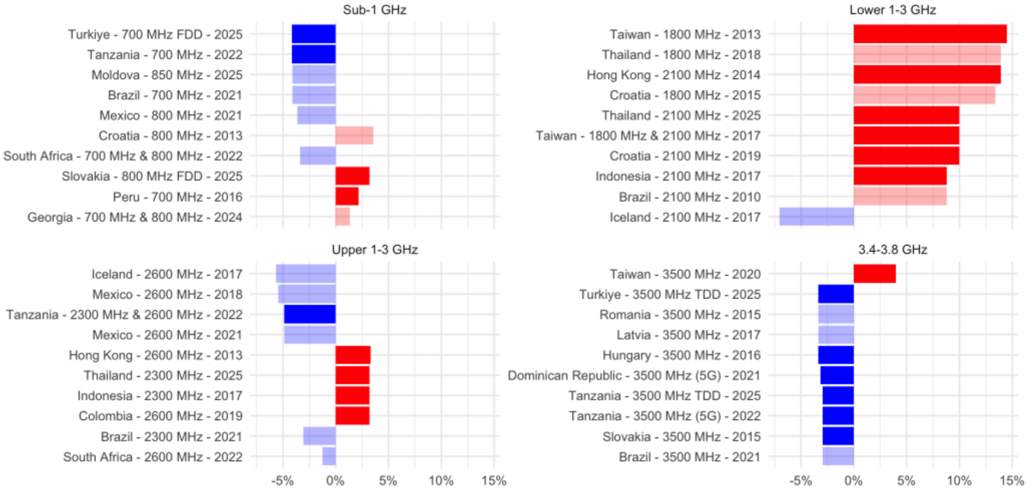
Lower 1-3 GHz	Singapore	1	-3.3%	-10.1%	-3.3%	-4.3%
Lower 1-3 GHz	Netherlands	1	-3.0%	-10.1%	-3.0%	-4.3%
Lower 1-3 GHz	Germany	1	-2.8%	-10.1%	-2.8%	-4.1%
Lower 1-3 GHz	Uruguay	1	-2.2%	-10.1%	-2.2%	-4.1%
Lower 1-3 GHz	Norway	1	-0.6%	3.0%	-0.6%	-3.3%
Lower 1-3 GHz	Switzerland	1	-0.3%	3.0%	-0.3%	-0.9%
Lower 1-3 GHz	Greece	1	0.1%	3.0%	0.1%	-0.2%
Upper 1-3 GHz	Hong Kong	3	-16.9%	-16.9%	-9.0%	-11.6%
Upper 1-3 GHz	Singapore	2	-9.9%	-9.9%	-7.9%	-9.1%
Upper 1-3 GHz	South Korea	1	-2.8%	-2.8%	-5.7%	-4.7%
Upper 1-3 GHz	Canada	1	-6.2%	-2.8%	-2.7%	-3.8%
Upper 1-3 GHz	Portugal	1	-2.8%	-2.8%	-3.0%	-3.8%
Upper 1-3 GHz	Uruguay	1	-6.1%	-2.8%	-2.6%	-3.7%
Upper 1-3 GHz	Turkiye	1	-2.8%	-2.8%	-2.5%	-3.7%
Upper 1-3 GHz	Finland	1	4.8%	2.8%	8.7%	3.6%
Upper 1-3 GHz	Lithuania	1	2.8%	2.8%	5.9%	3.6%
Upper 1-3 GHz	Nigeria	1	2.8%	2.8%	6.3%	3.6%
Upper 1-3 GHz	Romania	1	-2.8%	-2.8%	-2.3%	-3.6%
Upper 1-3 GHz	Thailand	1	-2.8%	-2.8%	-1.7%	-3.4%
Upper 1-3 GHz	United States	1	2.8%	2.8%	4.2%	3.3%
Upper 1-3 GHz	Sweden	2	3.0%	3.0%	3.2%	3.3%
Upper 1-3 GHz	Australia	1	2.8%	2.8%	3.8%	3.3%
Upper 1-3 GHz	Austria	1	2.8%	2.8%	2.5%	3.3%
Upper 1-3 GHz	Germany	1	2.8%	2.8%	2.6%	3.3%
Upper 1-3 GHz	Spain	2	0.2%	0.2%	2.0%	3.2%
Upper 1-3 GHz	France	1	-2.8%	-2.8%	-1.2%	-3.2%
Upper 1-3 GHz	Slovenia	1	-2.8%	-2.8%	-1.3%	-3.2%
Upper 1-3 GHz	Italy	2	0.0%	0.0%	0.7%	2.3%
Upper 1-3 GHz	Greece	1	2.8%	2.8%	0.8%	1.5%
Upper 1-3 GHz	Czechia	2	0.0%	0.0%	-1.0%	-1.2%
Upper 1-3 GHz	Norway	1	-3.0%	2.8%	0.6%	1.1%
Upper 1-3 GHz	Belgium	1	2.8%	2.8%	0.7%	1.1%
Upper 1-3 GHz	Croatia	1	2.8%	2.8%	0.4%	1.1%
Upper 1-3 GHz	Poland	1	2.8%	2.8%	0.5%	1.1%
Upper 1-3 GHz	Vietnam	1	2.8%	2.8%	-0.0%	0.6%
Upper 1-3 GHz	United Kingdom	1	-2.8%	-2.8%	-0.5%	-0.3%
3.4-3.8 GHz	United States	3	-10.8%	-12.8%	-10.8%	-8.1%
3.4-3.8 GHz	Canada	2	-7.3%	-7.7%	-7.3%	-4.9%
3.4-3.8 GHz	Bulgaria	1	5.7%	2.8%	5.7%	3.9%
3.4-3.8 GHz	Lithuania	1	3.1%	2.8%	3.1%	3.7%
3.4-3.8 GHz	Switzerland	1	2.5%	2.8%	2.5%	3.3%
3.4-3.8 GHz	Netherlands	1	2.2%	2.8%	2.2%	3.3%
3.4-3.8 GHz	Spain	2	3.2%	0.0%	3.2%	3.1%

3.4-3.8 GHz	Estonia	1	2.0%	2.8%	2.0%	3.1%
3.4-3.8 GHz	Nigeria	1	1.9%	2.8%	1.9%	3.1%
3.4-3.8 GHz	Greece	1	1.8%	2.8%	1.8%	3.1%
3.4-3.8 GHz	Slovakia	1	1.8%	2.8%	1.8%	3.1%
3.4-3.8 GHz	Portugal	1	-3.7%	-3.9%	-3.7%	-3.0%
3.4-3.8 GHz	Italy	1	-3.0%	-3.9%	-3.0%	-2.9%
3.4-3.8 GHz	Czechia	2	2.0%	5.6%	2.0%	2.9%
3.4-3.8 GHz	Finland	1	1.6%	2.8%	1.6%	2.9%
3.4-3.8 GHz	Australia	3	-2.0%	-3.9%	-2.0%	-2.9%
3.4-3.8 GHz	South Korea	1	-2.5%	-3.9%	-2.5%	-2.8%
3.4-3.8 GHz	Sweden	1	1.4%	2.8%	1.4%	2.8%
3.4-3.8 GHz	Poland	1	1.4%	2.8%	1.4%	2.8%
3.4-3.8 GHz	Latvia	2	10.7%	0.0%	4.2%	2.8%
3.4-3.8 GHz	Ireland	1	1.3%	2.8%	1.3%	2.5%
3.4-3.8 GHz	Croatia	1	1.2%	2.8%	1.2%	2.5%
3.4-3.8 GHz	Germany	1	-1.6%	-3.9%	-1.6%	-2.4%
3.4-3.8 GHz	France	1	-1.4%	-3.9%	-1.4%	-1.9%
3.4-3.8 GHz	Belgium	1	1.0%	2.8%	1.0%	1.8%
3.4-3.8 GHz	Moldova	1	0.9%	2.8%	0.9%	1.7%
3.4-3.8 GHz	Austria	1	0.8%	2.8%	0.8%	1.5%
3.4-3.8 GHz	Colombia	1	-1.2%	-3.9%	-1.2%	-1.3%
3.4-3.8 GHz	Hungary	1	-1.2%	-3.9%	-1.2%	-1.3%
3.4-3.8 GHz	Chile	1	-0.8%	-3.9%	-0.8%	-0.6%
3.4-3.8 GHz	Luxembourg	1	-0.7%	-3.9%	-0.7%	-0.4%
3.4-3.8 GHz	United Kingdom	2	-0.4%	0.0%	-0.4%	-0.4%
3.4-3.8 GHz	Norway	1	-0.6%	-3.9%	-0.6%	-0.3%
3.4-3.8 GHz	Uruguay	1	-0.4%	-3.9%	-0.4%	-0.3%
3.4-3.8 GHz	Singapore	1	-0.4%	-3.9%	-0.4%	-0.3%
3.4-3.8 GHz	Argentina	1	-0.3%	-3.9%	-0.3%	-0.2%
3.4-3.8 GHz	Hong Kong	1	-0.2%	-1.1%	-0.2%	-0.2%
3.4-3.8 GHz	Slovenia	1	-0.0%	2.8%	-0.0%	-0.2%

D.2 Price sensitivity to excluded awards

Next we consider the effect of adding the awards suggested by NERA/Aetha, as well as three additional 2025 awards from our SAD. The awards with the largest effect in each band group are in the figure below, followed by a table of the effect of including all suggested awards. Note that this is a hypothetical analysis of adding one additional award to the sample already used by the ACMA, not accounting for timing effects. For example, we do not have any reasons for excluding the Taiwan 1800 MHz award from 2013 from the sample, however, following Step 5 we filter out pre-2018 awards from the Lower 1-3 GHz band group, therefore it is not ultimately included in our recent benchmarks sample and does not affect price recommendations.

Figure 8: Changes to GHL statistic when adding awards



Faint bars are awards excluded for reasons set out in Annex C

Table 22: Changes to single price estimates as a result of adding awards

Band group	Observation	Step 6 price	Median	Geom. mean	GHL
Sub-1 GHz	Turkiye - 700 MHz FDD - 2025	-8.3%	-0.6%	-8.3%	-4.1%
Sub-1 GHz	Tanzania - 700 MHz - 2022	-5.2%	-0.6%	-5.2%	-4.1%
Sub-1 GHz	Moldova - 850 MHz - 2025	-3.7%	-0.6%	-3.7%	-4.1%
Sub-1 GHz	Brazil - 700 MHz - 2021	-3.2%	-0.6%	-3.2%	-3.8%
Sub-1 GHz	Mexico - 800 MHz - 2021	-2.6%	-0.6%	-2.6%	-3.6%
Sub-1 GHz	Croatia - 800 MHz - 2013	3.4%	0.6%	3.4%	3.6%
Sub-1 GHz	South Africa - 700 MHz & 800 MHz - 2022	-1.9%	-0.6%	-1.9%	-3.5%
Sub-1 GHz	Slovakia - 800 MHz FDD & 900 MHz FDD - 2025	1.9%	0.6%	1.9%	3.3%
Sub-1 GHz	Peru - 700 MHz - 2016	1.3%	0.6%	1.3%	2.6%
Sub-1 GHz	Georgia - 700 MHz & 800 MHz - 2024	0.6%	0.6%	0.6%	1.9%
Sub-1 GHz	Brazil - 700 MHz - 2014	-0.9%	-0.6%	-0.9%	-1.7%
Sub-1 GHz	Colombia - 700 MHz - 2019	-0.2%	-0.6%	-0.2%	0.2%
Lower 1-3 GHz	Taiwan - 1800 MHz - 2013	10.7%	3.0%	10.7%	14.5%
Lower 1-3 GHz	Thailand - 1800 MHz - 2018	9.4%	3.0%	9.4%	14.0%
Lower 1-3 GHz	Hong Kong - 2100 MHz - 2014	9.2%	3.0%	9.2%	14.0%
Lower 1-3 GHz	Croatia - 1800 MHz - 2015	7.5%	3.0%	7.5%	13.0%

Lower 1-3 GHz	Taiwan - 1800 MHz & 2100 MHz - 2017	6.2%	3.0%	6.2%	10.0%
Lower 1-3 GHz	Thailand - 2100 MHz - 2025	5.3%	3.0%	5.3%	10.0%
Lower 1-3 GHz	Croatia - 2100 MHz - 2019	4.2%	3.0%	4.2%	10.0%
Lower 1-3 GHz	Indonesia - 2100 MHz - 2017	3.6%	3.0%	3.6%	8.9%
Lower 1-3 GHz	Brazil - 2100 MHz - 2010	2.8%	3.0%	2.8%	8.9%
Lower 1-3 GHz	Iceland - 2100 MHz - 2017	-7.2%	-10.1%	-7.2%	-7.1%
Lower 1-3 GHz	Slovakia - 2100 MHz FDD & 1500 MHz FDD - 2025	-0.5%	-10.1%	-0.5%	0.0%
Lower 1-3 GHz	Colombia - AWS - 2013	-0.3%	-10.1%	-0.3%	0.0%
Upper 1-3 GHz	Iceland - 2600 MHz - 2017	-10.2%	-2.8%	-6.8%	-5.5%
Upper 1-3 GHz	Mexico - 2600 MHz - 2018	-2.8%	-2.8%	-4.8%	-5.4%
Upper 1-3 GHz	Mexico - 2600 MHz - 2021	-2.8%	-2.8%	-3.6%	-4.9%
Upper 1-3 GHz	Tanzania - 2300 MHz & 2600 MHz - 2022	-2.8%	-2.8%	-3.2%	-4.9%
Upper 1-3 GHz	Hong Kong - 2600 MHz - 2013	2.8%	2.8%	6.5%	3.3%
Upper 1-3 GHz	Colombia - 2600 MHz - 2019	2.8%	2.8%	3.5%	3.2%
Upper 1-3 GHz	Indonesia - 2300 MHz - 2017	2.8%	2.8%	3.7%	3.2%
Upper 1-3 GHz	Thailand - 2300 MHz - 2025	2.8%	2.8%	3.9%	3.2%
Upper 1-3 GHz	South Africa - 2600 MHz - 2022	-2.8%	-2.8%	-1.5%	-3.2%
Upper 1-3 GHz	Brazil - 2300 MHz - 2021	-2.8%	-2.8%	-1.4%	-3.0%
Upper 1-3 GHz	Brazil - 2600 MHz - 2012	-2.8%	-2.8%	-0.3%	-0.7%
Upper 1-3 GHz	Colombia - 2600 MHz - 2013	-2.8%	-2.8%	-0.5%	-0.7%
Upper 1-3 GHz	Colombia - 2600 MHz - 2023	2.8%	2.8%	0.8%	0.6%
Upper 1-3 GHz	Vietnam - 2600 MHz - 2024	0.9%	0.9%	0.1%	-0.6%
Upper 1-3 GHz	Slovakia - 2600 MHz FDD & 2600 MHz TDD - 2025	2.8%	2.8%	0.4%	0.3%
Upper 1-3 GHz	Georgia - 2600 MHz - 2024	2.8%	2.8%	0.3%	0.3%
3.4-3.8 GHz	Taiwan - 3500 MHz - 2020	5.3%	2.8%	5.3%	3.9%
3.4-3.8 GHz	Turkiye - 3500 MHz TDD - 2025	-6.2%	-3.9%	-6.2%	-3.4%
3.4-3.8 GHz	Romania - 3500 MHz - 2015	-5.2%	-3.9%	-5.2%	-3.4%
3.4-3.8 GHz	Latvia - 3500 MHz - 2017	-5.0%	-3.9%	-5.0%	-3.4%
3.4-3.8 GHz	Hungary - 3500 MHz - 2016	-5.0%	-3.9%	-5.0%	-3.4%
3.4-3.8 GHz	Dominican Republic - 3500 MHz (5G) - 2021	-4.6%	-3.9%	-4.6%	-3.2%
3.4-3.8 GHz	Slovakia - 3500 MHz - 2015	-4.4%	-3.9%	-4.4%	-3.2%
3.4-3.8 GHz	Tanzania - 3500 MHz TDD - 2025	-4.1%	-3.9%	-4.1%	-3.0%
3.4-3.8 GHz	Brazil - 3500 MHz - 2021	-3.9%	-3.9%	-3.9%	-3.0%
3.4-3.8 GHz	Tanzania - 3500 MHz (5G) - 2022	-3.9%	-3.9%	-3.9%	-3.0%
3.4-3.8 GHz	Vietnam - 3500 MHz (5G) - 2024	-2.4%	-3.9%	-2.4%	-2.6%
3.4-3.8 GHz	Vietnam - 3500 MHz (5G) - 2024	-2.4%	-3.9%	-2.4%	-2.6%

3.4-3.8 GHz	Georgia - 3500 MHz (5G) - 2024	-1.5%	-3.9%	-1.5%	-2.1%
3.4-3.8 GHz	Portugal - 3.6 GHz - 2021	1.0%	2.8%	1.0%	1.8%
3.4-3.8 GHz	South Africa - 3500 MHz (5G) - 2022	-1.4%	-3.9%	-1.4%	-1.7%

D.3 Time trends

We have re-run the one-sided Mann-Whitney U-tests of changes in price from 2018 onwards compared with pre-2018 for the revised sample. This confirms the same results as the ACMA has already found.

Table 23: One-sided Mann-Whitney test for a decrease in prices pre- and post-2018

	#Obs		
Band group	Pre 2018	2018 onwards	p value
Sub-1 GHz	33	39	0.000**
Lower 1-3 GHz	37	26	0.003**
Upper 1-3 GHz	26	18	0.837
3.4-3.8 GHz	5	50	0.991

Table 24: Two-sided Mann-Whitney test for a change in prices pre- and post-2018

	#Obs		
Band group	Pre 2018	2018 onwards	p value
Sub-1 GHz	33	39	0.000**
Lower 1-3 GHz	37	26	0.006**
Upper 1-3 GHz	26	18	0.337
3.4-3.8 GHz	5	50	0.018*

The two-sided Mann-Whitney test gives a statistically significant increase in spectrum prices for the 3.4-3.8 GHz band group at the 5% level. This result is based on a very small sample size and over-optimistic p-values; therefore we do not recommend the ACMA restrict the sample for this band group. We explicitly used the one-sided test in this report to test the stakeholder claim that spectrum prices have fallen.

Annex E Exchange rates

To benchmark spectrum prices across each of countries, we need a method to convert currencies across different years of award. The aim of comparing countries' spectrum award prices is to estimate at what level Australian operators value spectrum (in AUS dollars). This is primarily determined by how much (additional) revenue mobile operators can generate with the spectrum.

The conversion approach should reflect the underlying value of spectrum rather than short-term financial market conditions. In this context, two primary approaches are considered: spot exchange rates and purchasing power parity (PPP). We acknowledge that neither is perfect and explain our reasoning behind our recommended blended approach.

E.1 Definitions

E.1.1 Spot exchange rates

Nominal exchange rate, or spot rate, is the real-time market price of one currency in terms of another. It is determined by the global foreign exchange market and reported as the midpoint between the bid price and the ask price for a currency trade.

The spot rate reflects factors such as capital flows, interest rates, and market speculation, and can be highly volatile in the short run. It is used for immediate currency transactions and trade, and are widely used, well understood by stakeholders and readily observable.

E.1.2 PPP

Purchasing power parity (PPP) rates compare the buying power of different countries' currencies using a common basket of goods and services. Unlike spot rates, PPP accounts for price levels of both tradeable and non-tradeable goods and is not directly driven by the financial market.

PPP was developed to create a more accurate method for comparing standards of living and economic productivity across countries by accounting for differences in prices levels and currency valuation. The metric is reported every few years by the World Bank. Both the International Monetary Fund (IMF) and the Organisation for Economic cooperation and Development (OECD) use weights based on PPP metrics to make predictions and recommend economic policy.

E.2 Application to spectrum awards

Spot exchange rates and PPP both have their applications in real world problems. We must determine which is preferred regarding converting spectrum award prices for our benchmarking exercise.

E.2.1 Short vs long run considerations

The spot exchange rate is highly sensitive to short-run volatility due to trading on the forex market. This volatility is driven primarily by expected interest rate differentials across countries.[37] It means that spot exchange rates used for benchmarking may be sensitive to the precise dates chosen for converting price data. This could unexpectedly influence benchmarking prices. We do not expect spectrum award prices to be influenced by short-run fluctuations in currency exchange rates. While using annual averages (as reported by the World Bank[38]) mitigates some volatility, it does not eliminate the influence of short-run capital flows.

Convergence

In theory, PPP rates should represent a long-run position in which arbitrage between countries, either of tradeable goods or in the location of productive capacity creating goods and services, leads to price convergence. In practice, the timeframe for such convergence is very long and there can be costs to trade that prevent price convergence. Therefore, PPP is far from a perfect measure. It may represent a long-run equilibrium for

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[37] This is the Dornbusch overshooting effect. Given two identical countries with the same interest rates and a 1:1 exchange rate, if one country increases its interest rate, then its exchange rate will jump up instantly so that the exchange rate can then decline over time back to parity. This is necessary so that investors in both countries earn the same from holding domestic or foreign bonds, otherwise there would be strong capital flows. Notice that even the expectation of an interest rate change will induce an exchange rate jump.

[38] DataBank, World Bank

exchange rates that we never reach, in that other changes affect economies much faster than such price convergence can occur.

Revenues derived by mobile operators from spectrum ownership are realised over the length of the licence. Costs are also likely to be financed over a long period of time and hedged against exchange rate risk. The benchmarking methodology should prioritise long-term economic value over temporary market fluctuations.

E.2.2 GDP differences

PPP provides an advantage by correcting for differences in GDP. This ensures that spectrum prices are compared relative to the economic performance of the country rather than nominal market value.

The choice between spot and PPP impacts benchmarking results, particularly for a high-income nation like Australia. PPP inherently adjusts for Australia’s higher prices levels and greater purchasing power. PPP takes into account the fact that Australia is a high-income country therefore pushes benchmarks upwards, but this is appropriate as it reflects how much mobile operators benefit from the spectrum.

E.2.3 Revenues

Our benchmarking model must account for the varying revenues realised by operators within a currency zone (e.g. the Eurozone). PPP better captures the local purchasing power that ultimately drives the ARPU which justifies the spectrum investment.

E.2.4 Traded and non-traded inputs

PPP relies on a basket of goods influenced by non-traded inputs, such as local labour, rent and insurance. Because these costs aren’t traded globally, they are unlikely to reach international parity. This element in PPP rates contribute to their divergence spot rates in the short run.

Mobile operators’ face a similar cost structure, including both traded and non-traded inputs. Applying spot rates only considers traded inputs, and we expect that operators are protected against short-term exchange rate risks by long-term investment rates. Therefore, we expect PPP rates to reflect more accurately on operators’ input costs across countries than spot rates.