dot·econ

# Review of the ACMA expiring spectrum licence pricing

## Prepared for the ACMA

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# 1 Introduction

The ACMA has commissioned DotEcon to conduct a peer review of its benchmarking for estimating the market value of spectrum as input to setting appropriate renewal fees for expiring spectrum licences.

We have considered all aspects of the ACMA's benchmarking exercise[1] including the data used, the grouping of spectrum bands, and the nine-step process followed to establish price ranges.

Overall, our view is that the analysis conducted by the ACMA is reasonable. However, we believe there is scope for simplifying the analytical methodology, which then requires fewer assumptions and which may be more justified and easier to interpret. Along with a revised dataset to include additional awards, our recommended approach gives central price estimates that fall within or reasonably close to the ACMA's proposed ranges, though we find evidence to support increasing the price for the Upper 1-3 GHz band closer to the Lower 1-3 GHz and 3.4 GHz bands.

Table 1 gives an overview of the output of our analysis that is set out in more detail in subsequent sections. It shows the lower and upper ends of the ACMA's provisional price ranges, our central price estimates using the amended datasets (separately for all observations and recent awards only), alongside the lower and upper ends of the 95% confidence intervals (CI) of those statistics.[2]

[1] Set out in preliminary views paper 4 https://www.acma.gov.au/sites/default/files/2025-05/Preliminary%20views%20paper%204%20-%20Pricing%20for%20ESLs.pdf

[2] We have estimated the CI around the median using a bootstrapping method, where we resample the data with replacement and take the median of those samples. 95% of the sampled medians fall within the ranges shown.

*Table 1: Benchmarking summary – annual price estimates (AUD/MHzPop)*

| | | | ACMA provisional range | | Geometric mean (with 95% CI) | | | Median (with 95% CI) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bands | Sample | #Obs | Lower | Upper | Geom. mean | Lower | Upper | Median | Lower | Upper |
| Sub-1 GHz | All obs | 49 | 0.0690 | 0.0844 | 0.095 | 0.074 | 0.122 | 0.098 | 0.069 | 0.139 |
| Sub-1 GHz | 2018 onwards | 31 | 0.0690 | 0.0844 | 0.084 | 0.062 | 0.115 | 0.097 | 0.063 | 0.124 |
| Lower 1-3 GHz | All obs | 51 | 0.0209 | 0.0259 | 0.040 | 0.030 | 0.054 | 0.051 | 0.033 | 0.060 |
| Lower 1-3 GHz | 2018 onwards | 29 | 0.0209 | 0.0259 | 0.029 | 0.020 | 0.042 | 0.039 | 0.018 | 0.053 |
| Upper 1-3 GHz | All obs | 25 | 0.0065 | 0.0078 | 0.016 | 0.011 | 0.023 | 0.016 | 0.013 | 0.026 |
| Upper 1-3 GHz | 2018 onwards | 14 | 0.0065 | 0.0078 | 0.013 | 0.008 | 0.020 | 0.015 | 0.009 | 0.023 |
| 3.4 GHz | All obs | 47 | 0.0191 | 0.0241 | 0.021 | 0.015 | 0.029 | 0.020 | 0.013 | 0.030 |
| 3.4 GHz | 2018 onwards | 43 | 0.0191 | 0.0241 | 0.024 | 0.017 | 0.033 | 0.026 | 0.015 | 0.031 |

# 2 Benchmark data

*Competitive auctions*

Benchmarking uses price data from competitive spectrum awards, expressed on a per MHz per population basis and standardised to a common licence duration, to estimate the value of spectrum.

Prices in competitive auctions are typically determined by losing bidder's valuations, often for marginal spectrum blocks in auctions allowing bidders to acquire different amounts of spectrum. In auctions where significant amounts of spectrum go unsold[3], competition may be insufficient to raise prices above reserve price. These uncompetitive cases do not provide reliable information about market value and should not be considered for benchmarking purposes.

Administrative spectrum awards may contain some indirect information on market value if prices are based on, for example, a benchmarking exercise. In other cases, the objective of an administrative award may be other than to apply market prices. Therefore, administrative prices often do not provide genuine new information about likely market prices for spectrum, even if that administrative award was a licence renewal.

*Dropping data*

No competitive auctions should be excluded from a benchmarking exercise without good reasons, which are restricted to obvious errors or unavailability of data, or very strong *a priori* reasons to believe an award is irrelevant. This may include cases where, for example:

- use of the spectrum was restricted to specific use cases or technologies (e.g. fixed links), such that the licence price(s) could not be considered representative of the market value of a service and technology neutral licence in the same (or similar) band; or
- the auction was a residual award of a limited amount of unsold spectrum from a previous auction.

Trying to find more refined principles for excluding awards quickly becomes nebulous and difficult to apply on a consistent basis.

[3] Some spectrum auctions, especially with regional licensing or including multiple bands, may leave some lots unsold (for example, in commercially unattractive geographies). However, prices may still be competitively determined for the large majority of lots in main cases.

Transparent statistical methods can be used to ensure final price estimates are robust to outliers and appropriate for the Australian context without simply dropping observations at the outset.

*Multiband auctions*

Multiband auctions can be difficult to include if they are combinatorial, such that band specific prices do not exist. Even in non-combinatorial awards limited price information may be published (i.e. total payments by bidders for portfolios of various spectrum).

It is possible to infer reasonable estimates of band specific prices in these cases using details of the auction rules and results or detailed bid data in combinatorial awards (e.g. to estimate linear reference prices where both winning and losing bids are available in a combinatorial auction). However, it is rare that sufficient data is available and these awards often have to be excluded as a result.

*Data amendments*

We have reviewed the ACMA's benchmark data and suggested that some previously excluded awards should be included and that certain prices should be recalculated owing to data errors, mostly relating to the bandwidth awarded. These data revisions had only a small effect on price ranges.

*Annual fees*

The original ACMA dataset did not include annual ongoing spectrum fees where their level is not determined by the award, but for which the licensee is liable. The net present value of ongoing fees should be included if those fees are a direct result being assigned new spectrum, not simply a condition of being a telecoms operator. However, limited data is available on annual fees and only a small minority of awards can be reliably revised to include these fees. The effect on overall results is not material.

*Additional data*

Stakeholders have identified a list of awards that could be added to the ACMA's sample. We agree that it is generally appropriate to include these and have identified further additional awards of relevant spectrum that should be included using our Spectrum Awards Database (SAD). Annex A contains the list of awards we have added.[4]

*Results without filtering*

As discussed below, we believe the starting point when comparing award prices should be a simple, direct approach

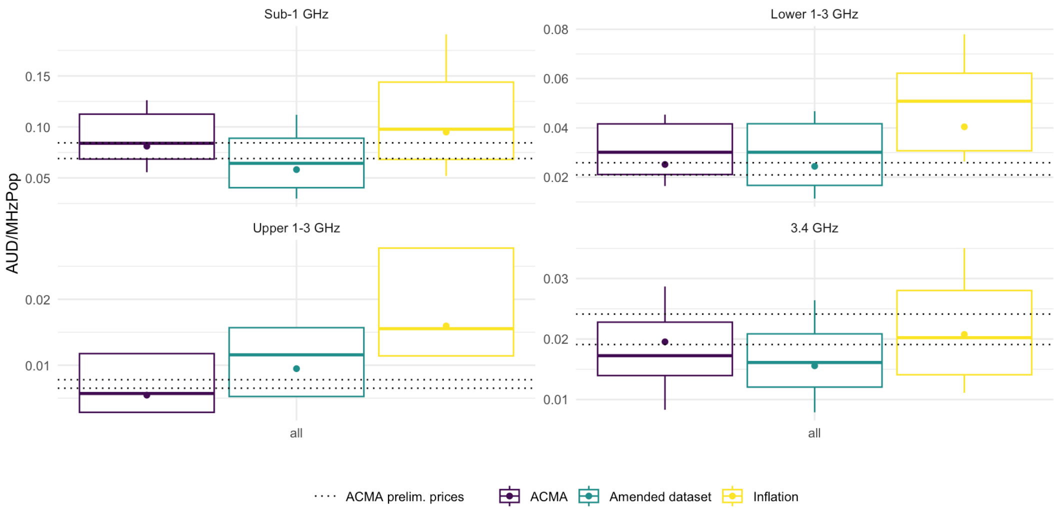
[4] The additional awards include those identified by Telstra (with the price points provided by Telstra incorporated directly into the analysis) and other relevant awards that we have identified (with benchmarks calculated using data stored in DotEcon's Spectrum Awards Database).

using real prices (i.e. adjusted for inflation, not the MSR index) converted to a common currency using PPP exchange rates. We use annual per MHzPop prices in 2025 Australian Dollars.[5] The figure below presents price ranges for all observations, first in the ACMA dataset, then in our amended dataset, including corrections and additional observations but without any changes to the methodology, and finally converting to real prices (instead of using MSR adjusted prices).

The boxplots can be read as follows, the:

- edges of the **box** are the custom percentile ranges defined by the ACMA (which differ by band group);
- **whiskers** are the interquartile range (these are absent for the Upper 1-3 GHz bands as the ACMA range is wider than the IQR);
- the **line** across the box is the median;
- the **point** shows the geometric mean; and
- the **dotted lines** across the box are the provisional price ranges proposed by the ACMA.

*Figure 1: Impact of data/methodology revisions on benchmarking results*




Adding further data tends to reduce prices in the Sub-1 GHz and 3.4 GHz bands. Using an inflation adjustment, rather than

[5] To adjust for inflation, we first convert prices into US Dollars, using the PPP exchange rate from the award year. We then adjust for US CPI, giving prices in 2025 US dollars, before converting into Australian Dollars using the 2025 US-Australia PPP exchange rate.

the MSR index tends to raise prices, especially of bands that tend to be awarded early. The combined effect is to:

- leave the median of the sub-1 GHz band close to the upper end of ACMA's provisional range;
- leave the median of the 3.4 GHz band at the lower end of ACMA's provisional range;
- raise estimates for the Lower and Upper 1-3 GHZ groupings closer to the 3.4 GHz benchmark.

These results are before any consideration of time trends in spectrum value, which we consider below.

# 3 Measurement issues

## 3.1 Coverage and population density

*Exceptionally low population density*

Deploying networks over large sparsely populated areas is more costly on a per user basis. The value of spectrum might therefore be expected to be lower in countries with a low population density. Australia has the lowest population density of any of the countries in the award data.

However, the relationship between population density and spectrum value is complex and depends strongly on the coverage obligations applied over the sparsely populated areas. There has historically been no formal requirement or expectation that operators will deploy networks in the deeply rural areas of Australia, and indeed these areas have been excluded from regional awards of spectrum in some bands. Therefore, Australia’s headline population density likely understates the density in the areas relevant to spectrum licensing by including low density areas where terrestrial network deployment will likely never happen.

*US and Canadian benchmarks*

Some stakeholders have suggested removing US and Canadian auction with high prices from the dataset. However, these benchmarks are highly relevant as the two countries are among the most similar to Australia, being high income countries with large landmasses. This is especially true of Canada given its similarity to Australia in terms of population density.

Ultimately, the density of the areas where operators will deploy networks is more relevant than country level population density, while the latter is a reasonable proxy absent more detailed data, but should be used with caution.

*Coverage obligations*

Coverage obligations are often a feature of spectrum awards, sometimes as a lightweight measure to protect competition between operators and to ensure that spectrum is actually put to use, and other times as an interventionist measure to force deployment in geographic areas that would not otherwise be served by competing operators. Interventionist coverage obligations can significantly affect spectrum value, by inducing a cross subsidy from the profitable areas to those uneconomic to serve.

The impact of coverage obligations and the effect of population density more generally, can be expected to vary across bands.

Population density might have a greater effect on the value of lower frequency bands, which are used to meet coverage needs. However, in some cases higher frequency bands, which are not typically used for wide coverage deployment, could have their value raised where there is additional demand created by use for wireless local loop (WLL) in rural areas.[6]

## 3.2 Exchange rates

*Advantages of PPP rates*

For converting award prices into a common currency (AUD), either PPP or spot exchange rates can be used. Neither is perfect, but our recommendation is to primarily use PPP.

PPP is calculated by comparing the pricing of a reference basket of goods across countries. 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 exchange rates that we never reach, in that other changes affect economies much faster than such price convergence can occur.

Whilst PPP exchange rate data is subject to both conceptual and measurement issues, it is nevertheless attractive as it eliminates the impact of short-run exchange rate volatility. This volatility is driven primarily by expected interest rate differentials across countries.[7] It means that spot exchange rates used for benchmarking may be sensitive to the precise dates chosen for converting price data.

*GDP differences*

A further advantage of using PPP rates is that it, to some degree, corrects for GDP differences. Higher income countries

[6] This is primarily an issue for 3.4 GHz and 2.6 GHz results.

[7] 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.

tend to have higher consumer prices, which PPP rates correct for.[8]

*Intersecting price ranges*

The price ranges that the ACMA report are based on intersecting ranges derived separately under spot and PPP rates. This creates a narrow ranger than if a single exchange rate assumption were used.

In our view, intersecting the two sets of results under different exchange rate assumptions is difficult to justify. If the ACMA is agnostic between the use of PPP and spot rates, taking the intersection does not make the results less certain and it would be more justifiable to use the union of the two ranges. Our preferred approach would be to primarily use PPP rates (for the reasons outlined above) and use spot rates only for a cross-check. For this reason, we have focussed on results using PPP rates in the reporting below.

## 3.3 Standardising licence lengths

*Flat annuity approach*

Benchmark data consists of licences with different lengths. These need to be standardised in some way, which requires some assumptions about the time profile of profitability benefits from licences. The ACMA has adopted a flat annuity approach, using a post-tax nominal WACC of 8.49%[9] as the discount rate, to convert benchmark prices to a notional single-year valuation.

The flat annuity approach assumes that the licence holder receives a stream of benefits that is constant in *nominal terms* over the duration of the licence. The annuity value is that which, as an annual profit stream, yields a net present value equal to the licence price over its duration using the assumed discount rate. Assuming a constant nominal profit stream means that the *real* benefit of spectrum to the licensee (i.e. after stripping out inflation) is assumed to be falling over the duration of the licence. Typical long-run inflation expectations for Australia are currently around 2-3%, so this is the implied rate at which real benefits of the licence decline.

[8] This is the Balassa-Samuelson effect. If countries differ in productivity, price equalisation of traded goods will leave a price differential, for non-traded goods with the more productive country have a relatively higher price for non-tradable goods.

[9] This is based on advice from two independent studies conducted by Frontier Economics and Ian Martin Advisory.

*Sensitivity*

If, hypothetically, all our benchmark data had licences of the same length, then none of these assumptions would matter at all. The corresponding annuity value for each licence would be some proportion of its price, with this proportion being the same for all licences. The proportion depends on the assumptions of the annuity model (i.e. phasing of benefits to the licensee and discount rate). Because we are converting benchmarks to annuity values and then eventually back to recommended licence prices, this proportion is irrelevant in this case.

Once licences have different durations, the ratio of the annuity value to the licence price varies with length (a smaller proportion for longer licences). However, most licences are around between 15 and 20 years in length so the impact of normalising for length differences on the eventually recommended prices is small and the assumptions behind the annuity model are not critical.

Our view is that use of a flat annuity approach is reasonable, in the absences of any strong priors about the time distribution of value derived from licences (i.e. whether this increases or decreases over time). Whilst, in reality, the value to users will likely vary across the licence term, the pattern of variation is unknown, unobservable and will likely vary across licences.[10] It could be argued that assuming constant *real* benefits might be more reasonable as a starting position in the absence of specific information to inform the annuity model, in which case a real discount rate (i.e. a lower real WACC around 5.5-6.5% per annum) might be more appropriate, which would lead to slightly larger adjustments when standardising for licence duration differences. However, this would not have a material effect on the end results.

We discuss the question of consistency of assumptions about this distribution of value over the licence term with data on trends in spectrum value later (when considering the MSR index), but for now we note that there is nothing in that subsequent discussion to suggest that the flat annuity approach using a nominal WACC is unreasonable.

*Choice of WACC*

We are also of the view that use of a single WACC value for these purposes is sensible. As the ACMA acknowledges, a country/year specific WACC for each award would be ideal, but

[10] For example, licences for newly awarded spectrum may have limited value at the start of the licence whilst infrastructure is being deployed, whereas renewals of pre-existing licences are more likely to yield value immediately.

it is not realistic to obtain this data. In any case, we would not expect either the specific choice of WACC (within a reasonable range) or the use of multiple WACCs across different observations to make a significant difference to the outcome. We do not see any obvious issues with the ACMA's choice of WACC value as the end results are not particularly sensitive to the choice, especially given the other uncertainties involved.

*Indefinite licences and renewals*

In some countries licences have been awarded for an initial term but with licensees being given a strong expectation of licence renewal, or possibly with licences being considered indefinite. This clearly increases the value of the licence. However, renewals would typically not be expected without having to pay further fees, which would often be set based on estimated market value for the spectrum at that time.[11] Therefore, we agree with the ACMA's approach of using the initial licence term as the licence duration in these cases.

[11] Of these countries, the US gives the clearest guidance on the conditions for licence renewal and would have the strongest case for being treated as if it had a longer notional licence duration. However, this would still require some implicit assumption on the uncertain valuations placed on spectrum in the distant future, which risks being overly arbitrary and inconsistent with how other countries are treated, without bringing much benefit if the overall methodology is robust to outliers. We recommend that the ACMA uses initial licence duration for all countries, including the US.

# 4 Time trends

## 4.1 Inflation

*MSR index*

Inflation is not considered explicitly in the ACMA's analysis, which is all in nominal terms, though it enters implicitly via the nominal WACC and assumed time trends of future spectrum prices. The ACMA has used a revenue/MHzPop index (the "MSR index") to adjust nominal prices over time.

Whether the MSR index is increasing or decreasing depends on the time window considered. We note that this index is bound to fall after a significant award of new spectrum, as the available MHz increases before operators' revenue increases. The effect on individual observations that fall either side of an Australian spectrum award is mitigated by taking three year rolling averages, but this does not resolve the more fundamental issue that such short-run changes should not be taken to indicate a sustained trend in spectrum values. Therefore, it is necessary to take a broad view over longer time periods for this approach to be reasonable.

*Movements in prices over time*

Movements in spectrum prices are driven by complex mix of factors. The question of long-term price movements is, therefore, primarily an empirical one.

We have adopted the somewhat simpler approach of first looking at real prices (i.e. after correction for inflation) and then considered as a second step whether there is evidence of time trends in *real* spectrum prices that need to be overlaid before reaching conclusions on recommended spectrum fees. There should be statistically significant evidence of changes to real prices over time to warrant making any adjustments to benchmarks.

*Supply and demand changes*

Trends in spectrum prices are a function of both supply and demand changes. There has been an increase in the supply of spectrum through band clearance and refarming. It is possible that in earlier awards bidders may not have fully anticipated, or placed a risk premium, on subsequent spectrum releases. This effect would tend to put a premium on the value of spectrum issued in earlier awards, but not greatly affect the value of spectrum in later awards, at which point supply of spectrum was already more certain. From a supply perspective, the context for renewals is similar to that of more recent awards.

The extent to which bands are substitutes, either for meeting coverage or capacity needs, may also affect supply possibilities. Moves towards increasing allocation of spectrum as TDD spectrum should increase substitutability of higher bands (> 1 GHz) but lower frequencies will always be limited substitutes for higher frequencies because of propagation characteristics. Therefore, different bands are best considered as a *chain of substitutes*. This allows for, but also limits, price differentials between them.

At the same time, demand for spectrum is driven by increase in mobile connections (including M2M and consumers with multiple devices) and data growth. Working against this, there has been progressive adoption of more spectral efficient technologies, increasing throughput per MHz of spectrum used. Therefore, net effects on price of these various supply and demand trends are potentially ambiguous. We need to consider the available empirical evidence.

## 4.2 Treatment of future expectations

*One-year prices*

Before considering whether there are any trends in spectrum valuations, it is important to consider what a one-year (annuity) value in the benchmarking data represents. This is *only* used as a calculating step to allow benchmark data points to be standardised to match the length of licences being awarded by the ACMA. It is *not* an implicit rental price for access to spectrum for one year.

All the prices being considered include expectations of value held at the time of the award looking forward over the typical licence duration. Even if a licence price is annuitized into a one-year value it still includes these expectations.

These forward-looking valuations formed by bidders would also incorporate expectations of growth in population and prices. Therefore, the ACMA's proposal to work in $/MHz/Pop prices and then to calculate prices based on population at the time is reasonable, as is working in real terms.

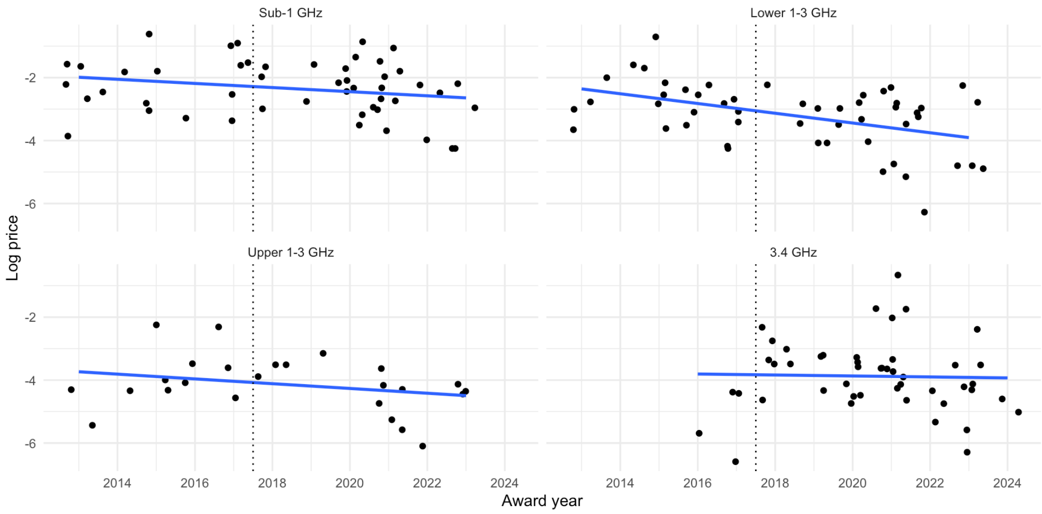
*Using recent benchmarks only*

Therefore, it is not clear that future prices need explicit modelling at all, as benchmark data is for long-term licences that already include within them expectations of future spectrum value. In particular, even if there are underlying trends in spectrum value, simply looking at recently concluded awards provides a basis for valuing spectrum soon to be awarded, as trends will have had insufficient time to affect valuations. We only need to worry about future price trends if we are trying to forecast licences which start significantly in the future.

Clearly past valuation trends may be relevant if we are looking at benchmark data over a long time period, where early and late awards may differ systematically due to those trends. However, providing there is sufficient data, we can always strip out such trends or more complex movements by considering only recent benchmarks.[12] This provides a much simpler approach than use of the MSR index and avoids making any detailed assumptions about the nature of any valuation trends – we discuss our concerns around the MSR index in more detail in the following section.

## 4.3 Long-term price trends

*Figure 2: Time trends in observable prices*




The figure above shows the natural logarithm of real prices over time for each band grouping. The data supports a view in which market prices of all bands, other than the more recently

[12] For example, the ACMA's decision to look only at awards from 2013 onwards means the benchmarks are not affected by the auctions from the early 2000s that saw very high prices owing to bidders' expectations at the time. We must also be careful about comparing renewals that have taken place since 2013 to the original award from that time when prices were inflated – lower prices at renewal in that case are not necessarily evidence of a structural feature of licence renewals.

allocated 3.4 GHz spectrum, have fallen in real terms over the relevant period.

*Sub-1 GHz*

Sub-1 GHz spectrum has fallen by less than 1-3 GHz spectrum. This is probably because of the fundamental long-term constraints on finding any additional spectrum in substantial amounts other than through UHF TV band release.

*Tests for price trends in 1-3 GHz groups*

We ran non-parametric Mann-Whitney U-tests[13] to investigate differences between earlier and more recent observations.

- First, we split the sample into pre-2018 and post-2018 (as shown by the dotted line above). This roughly divides the data in half, except for the 3.4 GHz awards which tend to be later (and for which there is no evidence of a trend in price).[14] We only found a significant fall for the Lower 1-3 GHz bands.
- Second, we also split the observations into rough thirds by time, and found a significant difference between the earliest and most recent third for both 1-3 GHz band groupings.

We take these results as providing evidence for a decline in real prices for the Lower 1-3 GHz band and somewhat weaker evidence of a decline in real prices for the Upper 1-3 GHz band.

*Forward-looking trends*

Whilst there is evidence of trends over the sample period, we cannot assume that a similar downward trend will continue. During the sample period there was both re-award of previous allocated bands (1800 MHz, 2.6 GHz) on a newly liberalised basis and introduction of entirely new bands (e.g. 2.3 GHz, 3.4 GHz) adding substantial additional bandwidth. Looking forward now, additional spectrum release for cellular networks above 1 GHz is primarily expected in the mmWave bands. These bands may be significantly less substitutable for spectrum below 3 GHz both because of limited propagation and heavy power demands on mobile terminals. At the same time, demand for bandwidth is expected to continue to grow with data traffic.

[13] A non-parametric test that the prices in the different band groups are drawn from the same distribution. Specifically, we ran one-sided tests using a 5% significance level. See Annex B for detailed results.

[14] When selecting a cut-off point in time to define recent awards, there is a trade-off between focusing on the most recent awards and maintaining a sufficient sample size to calculate robust statistics. We use 2018 as the cutoff, which is the last year that allows us to keep at least half of the observations for all band groups in the 'recent' sample. There is no clear reason to choose different years for different band groups. 2018 also has the benefit of 5G 3.4 GHz awards having begun (but still being in their early stages), so expectations over spectrum supply would be relatively stable.

This may weaken and potentially even reverse the downward trend in real prices seen over the sample period. Therefore, there is substantial uncertainty around any projection of this trend out beyond the near term.

*Convergence of upper/lower 1-3 GHz prices*

There is some evidence in the data that Lower 1-3 GHz spectrum was at a price premium over Upper 1-3 GHz spectrum early in the sample period, but that this difference has been largely eliminated by the end of the period. This may be due to observations for bands in the Lower 1-3 GHz group including re-award (and liberalisation) of 1800 MHz and 2.1 GHz bands that were already in use, and for which networks were already geographically dimensioned. As other bands in the 1-3 GHz range have become available, this distinction has diminished. All bands in this range are increasingly substitutes to deliver capacity and are converging in price. Nevertheless, this convergence is not complete and prices in the Lower 1-3 GHz bands still remain statistically significantly above those in the Upper 1-3 GHz bands (discussed below).

*Restricting to later data*

Given this, a simple approach is to look only at benchmarks later in the period. These should better reflect current spectrum values, regardless of exactly what trends are in operation during the entire period. On this basis, value differences between the Lower 1-3 GHz, Upper 1-3 GHz and 3.4 GHz groups are smaller than the ACMA’s current proposed ranges suggest. This suggests there is room to set a somewhat higher fee for Upper 1-3 GHz spectrum.

# 5 MSR index

As discussed in the previous section, the ACMA has undertaken its benchmarking exercise in nominal prices (i.e. without correction for inflation) and then applied an index calculated from mobile service revenue (MSR) to try to standardise benchmarks from different years to current terms. This index tries to estimate the underlying trend in *nominal* spectrum prices and also implicitly corrects for inflation.

We are unconvinced that an index based on contemporaneous mobile revenue is a reliable means to model underlying movements in spectrum prices, as discussed below. In our view, it is better to look *directly* at whether the historical data contains evidence of trends in spectrum prices. It is also more transparent to split out inflation and consider *real* spectrum prices.

## 5.1 Conceptual problems with MSR

*Revenues vs spectrum prices*

An objection to the MSR approach is that spectrum prices represent the expected future profitability impact of spectrum over the duration of the licence term, of which contemporaneous mobile revenue is a contributor.

Spectrum prices depend on expectations about operators' future profitability without and with spectrum, with profitability in turn being the *difference* between future revenue and costs. Spectrum value represents a long-term expected view of operator profitability many years forward.

It is reasonable to expect that spectrum prices are positively correlated to contemporaneous mobile revenue, not least as expected future revenue (and future profitability) may be positively correlated with current revenue. However, spectrum prices need not track contemporaneous mobile revenue proportionately.

*Awards depress MSR in the short term*

A further problem with the MSR index is that it divides contemporaneous revenue by spectrum holdings. After an award, spectrum holdings necessarily increase. However, there is very unlikely to be any immediate positive impact on operators' revenue from spectrum acquisition, not least as associated network deployment is needed to use the spectrum. In some cases, most of the existing stock of handsets held by subscribers may not be able to use new frequency bands and benefits only occur as handsets are upgraded.  Therefore, there is likely to be a substantial lag in any revenue benefit.

Furthermore, the benefit to an operator from additional spectrum is not necessarily realised as additional revenue, but rather as reduced cost through not having to build additional base stations.[15]  In spectrum valuation models, the large majority of spectrum value typically comes from the avoided cost of additional network equipment that would be required to meet expected data traffic projections in the counterfactual in which that spectrum is not won.

For these two reasons, it is therefore, inevitable that the MSR index will fall as new spectrum is awarded, as the number of MHz held increases and any effect on revenue is deferred. This is only partially addressed by calculation of moving averages as the averaging period of 3 years is much shorter than the likely time needed for any revenue benefits to work through. Averaging does nothing to address the issue that spectrum value may derive from cost savings, rather than revenue gain.

*Downward bias in the MSR*

Indeed, if adding spectrum to some extent reduces network costs, not just increasing operators' revenues, then the MSR index would *necessarily* decline relative to spectrum prices. Therefore, the MSR index is not a good proxy for movement in spectrum prices in the short term and will tend to create a systematic downward bias.

Spectrum awards tend to occur in pulses as new bands are released. This can lead to arbitrary differences in the adjusted prices of similar awards. New spectrum release necessarily forces the MSR index down. There are then similar awards that follow soon after, which take the lower MSR index as a base and therefore receive different adjustments, despite there having been no material change in circumstances since the earlier award, as there has been insufficient time for any revenue benefit of the earlier awards to be seen.

[15] Network capacity derives from the combination of an amount of spectrum and a number of base stations. Operators need some base level of spectrum and equipment to operate (at all or in a new band), but by acquiring *incremental* spectrum, an operator can expand capacity at a lower cost and this avoided cost for a given level of capacity contributes to the value of the spectrum.

# 5.2 Inflation

Most economic analysis involving multiple time periods typically uses *real prices*, standardised to some reference year. This provides direct comparability of prices in datasets that span many years.

*Consumer baskets*

Measures of inflation created by statistical agencies involve tracking some basket of goods and services over time, reflecting average consumption patterns of consumers (which may change, requiring updating of baskets). As baskets include sufficient goods and services to cover most of typical consumers' expenditure, such indexes measure widely averaged price movements and are intended capture the trend in the *overall* level of prices.  Some special-purpose indexes may exclude certain expenditure components (e.g. housing costs), but are still broad-based.

In this report, we have first converted foreign spectrum prices to US Dollars at the applicable PPP exchange rate at the date of the award.  These nominal prices in different years are then converted into current prices using an US deflator before final conversion into AUS dollars.

*CPI is still relevant even though spectrum bought by operators*

Radio spectrum is not a service directly purchased by consumers, but consumer price indices are still relevant in considering how the *nominal* market value of spectrum will change over time. A general increase in prices of consumer goods will be accompanied by increases in wages and changes to exchange rates that, absent other changes, leave *relative* prices largely unchanged in the long run. Therefore, in the long run, spectrum prices should reflect general inflation, as the *nominal* amount that operators can charge for their services and the *nominal* costs they incur will have all increased proportionately, despite spectrum not being directly purchased by consumers.

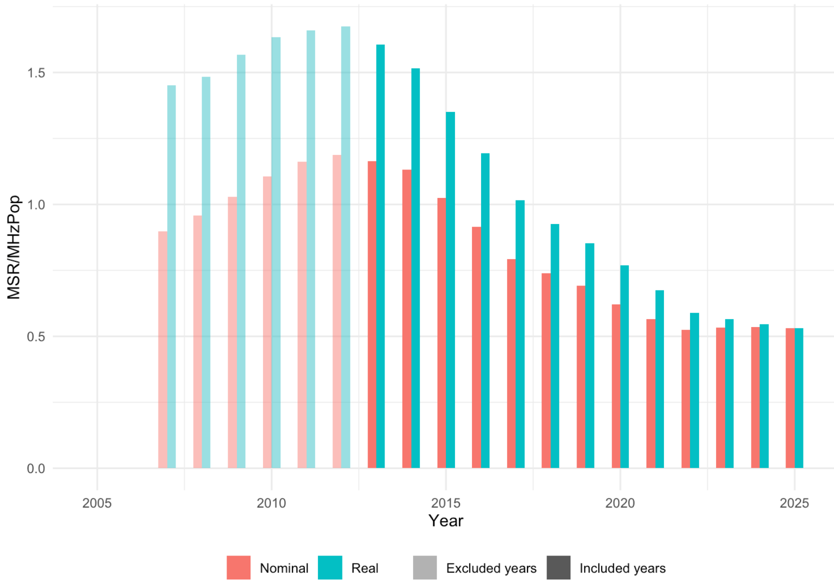
Correcting spectrum prices for inflation merely removes changes in the *general* price level of goods and services in the Australian economy.  It does not preclude subsequent consideration of whether there are reasons that there could be changes in *real* spectrum prices, which amount to a change in the *relative* price of spectrum to other goods and services (including other inputs that mobile operators might purchase).

## 5.3 MSR and real spectrum prices

*Real MSR movements*

The MSR index reported in Figure 18 of the ACMA report[16] is expressed in *nominal* prices. This can also be expressed in real terms, which strips out the effect of inflation in boosting nominal prices from older benchmarks. This more clearly shows the assumed dynamics of *real* spectrum prices implied by the MSR approach. This is shown in Figure 3 below, using Australian CPI to deflate the nominal MSR index values[17].

*Figure 3: Real and nominal MSR index (for historic years only in 2025 base)*




*Note: Excluded years refers to the fact that pre-2013 observations are excluded from the benchmarking analysis. MSR values taken from the 3-year rolling average.*

From the figure above, we can see that the MSR approach presumes that there has been a steep decline in spectrum prices during the period of the benchmarking analysis (2013 onwards), falling from a peak around 2012. This is a very strong effect, with *real* MSR index falling to about one-third of the peak value. The effect on benchmarking is to strongly discount awards in the first third of the sample. Real prices from 2013 (the first year used in the benchmarking analysis) are reduced by 67% and

[16] Preliminary views paper 4

[17] [https://www.abs.gov.au/statistics/economy/price-indexes-and-inflation/consumer-price-index-australia/jun-quarter-2025](https://www.abs.gov.au/statistics/economy/price-indexes-and-inflation/consumer-price-index-australia/jun-quarter-2025)

prices from all years before 2018 are reduced by more than 40% by applying the MSR adjustment.

*Implications of the benchmark data*

As we discuss below, there is no mechanical link between movements in the MSR index and movements in spectrum prices. Therefore, we need to consider what evidence of trends can be seen *directly* from the benchmark data. In Section 4.3, we showed the trends in real spectrum prices (see Figure 2), the main features of which are summarised in Table 2 below.

*Table 2: Trends in real spectrum prices 2013-2025*

| Band | Average annual trend in real price over 2013-2025[18] | Total reduction in real price 2013-2025[19] | p-value of one-sided test against null of no trend |
|---|---|---|---|
| **Sub-1 GHz** | -6.6% | 48% | 0.059 |
| **Lower 1-3 GHz** | -11.1% | 67% | 0.004 |
| **Upper 1-3 GHz** | -7.6% | 53% | 0.095 |
| **3.4 GHz** | -1.5% | 12%[20] | 0.427 |

From Table 2, we can see that there are material downward trends in the real prices of the two 1-3 GHz groupings, but a much smaller trend for sub-1 GHz spectrum. Only the Lower 1-3 GHz band has a statistically significant trend (at the 5% level), though the Upper 1-3 GHz and Lower 1-3 GHz trends are weakly significant (at the 10% level). The 3.4 GHz band has a much weaker trend and this is not statistically significant.

Therefore, we conclude that:

[18] This is the interpretation of the coefficient of a regression of the log price on the award year, i.e. the slope of the best fit line in Figure 2.

[19] The implied percentage difference in prices between the two ends of the best fit lines shown in Figure 2.

[20] The earliest 3.4 GHz award in the sample is from 2016. The MSR index fell by 56% between 2016 and 2025.

- There is some evidence of downward trends in real spectrum prices the bands below 3 GHz, but only the Lower 1-3 GHz band sees as a large a decline over the 2013-2025 as the MSR index suggests (67%);
- The important Sub-1 GHz band sees a much smaller decline than the MSR index suggests, most likely as there are fundamental limitations in the supply of suitable spectrum in this range;
- There is no evidence at all from the benchmark data of a trend in real prices of 3.4 GHz spectrum.

*Trends differ across bands*

For these reasons, we conclude that it is not appropriate to apply the MSR index *uniformly* across all four band groups to downrate more recent spectrum prices. To do so likely leads to an underestimate of current prices, especially for sub-1 GHz and 3.4 GHz bands. However, equally there is some evidence of systematic changes to real spectrum prices over time *for some bands*. Therefore, there is a reasonable case for focussing on more recent awards when setting future spectrum fees, due to the risk that older awards may be unrepresentative.

*Filtering*

We consider that the approach of filtering the benchmark data to look at only recent (i.e. 2018 onwards) benchmark data is superior to the MSR approach for several reasons:

- It allows for the possibility of differential price movements over time across the different bands (which the data suggests is the case);
- It does not presume any particular form for price movements over time;
- It makes explicit that the need to focus on more recent awards entails greater uncertainty about average prices (due to reduced the sample size).

At least in principle, it may be possible to capture trends over longer periods through a systematic econometric model. However, we have not attempted this as it would require significant investigation of the appropriateness of the fit of such a model to the data. Simply taking more recent benchmarks provides a simpler approach.

## 5.4 Projections of the MSR index into the future

We now turn to the question of assumed future trends in the MSR index. The ACMA has assumed that the (nominal) MSR index will remain constant in future. This means that future spectrum prices are implicitly assumed to fall in real terms at the expected inflation rate (i.e. roughly 2-3% per annum).

This assumption features in the ACMA's analysis in two ways.

- First, there is a question of consistency between assumptions about the assumed trends in spectrum prices and the assumed time distribution of benefits during the term of licences (i.e. the 'annuity model' used to standardise different licence durations).
- Second, for calculation of a recommended price for a licence commencing at some point in the future.

*Relationship between spectrum price trends and annuity model assumptions*

We have already discussed the annuity model at some length above and noted that its assumptions are not critical to end results. The ACMA has assumed a flat annuity in nominal terms, which implies that the flow of benefit to the licence holder over the duration of a licence is declining in real terms (at the expected inflation rate).

There does not need to be a precise match between assumptions about the time distribution of licence benefits (the annuity model) and trends in spectrum prices, but the latter needs to reflect the former over the long run. Clearly the ACMA's current approaches to the annuity model and *assumed future* spectrum price trends are consistent, as both assume constancy in nominal terms (and so decline in real terms). However, the annuity model assumptions differ significantly from the *historic* price trends applied to the benchmark data, which for some bands assume faster falling real prices.

*Tilted annuity model*

We can see from Table 2 that the benchmark data suggests that, except for the 3.4 GHz band, there is some evidence of declines in *real* spectrum prices at faster rates than typical inflation expectations of 2-3% per annum. By implication, this suggests that the benefits of spectrum licences could be more front-loaded than assumed by a flat (nominal) annuity model. Imagine a flow of benefit from spectrum that can change over time. This determines a price for a licence, equal to the PDV of this flow benefit between the start and end of the licence. The time trend in the licence price is then the (weighted) average trend in the flow benefit over the duration of the licence. It is sufficient (but not necessary) that the flow benefit declines for spectrum price to decline. The flow benefit can increase during sufficiently short periods providing that when averages are taken over a typical licence duration there is a net fall. Therefore, falling spectrum prices do not require falling flow benefits at all times. Nevertheless, they impose a requirement for average decline of flow benefits over licence period. If we additionally assume that flow benefits do not change too quickly, then they need to fall uniformly. In this case, a tilted annuity model might be preferrable and smaller adjustments should be made for differences in licence duration than are currently applied.

Ultimately such changes would have little effect on end results, so we do not consider this issue further given its lack of materiality. Furthermore, estimates of the magnitude of real price trends are highly uncertain. We would also add significant complexity – without adequate justification from the benchmark data – if we used different annuity models for different bands reflecting different trends in spectrum prices.

*Downrating for deferred start dates*

The second issue is whether to discount recommended licence prices to reflect deferred start dates. The licences being benchmarked would start between 2028 and 2032. Therefore, any assumed continued time trend in spectrum prices would have between 3 and 7 years to be applied to any estimate of *current* market prices and so is potentially material.

At present, the ACMA's approach is to fix prices in nominal terms when it assumes that the future MSR index remains constant. This implies a decline in real spectrum values due to expected future inflation, which might reasonably be expected to be around 2-3% per annum. However, looking at Table 2 above, we can see that downrating real prices at this rate is arguably too great for the 3.4 GHz band and possibly not great enough for the Upper and Lower 1-3 GHz bands.

As we have already noted above, the estimated *historical* annual trend for each band is subject to considerable uncertainty and it would be difficult to reject the ACMA's current approach (i.e. an implicit downrating of real prices of around 2-3% per annum) from the data alone. Furthermore, we have no guarantee that any such estimates of historical trends can be extrapolated into the future.

*Are historic trends good pointers to the future?*

Indeed, the fact that we find no significant trend for 3.4 GHz prices is suggestive that trends in the other bands may not be stable and likely to persist. We have already discussed that in earlier awards there may have been only partial anticipation that future awards would increase spectrum supply or an element of risk aversion not relying on later awards providing more spectrum. Therefore, falling (real) spectrum prices may not be due to fundamental changes in the balance of supply of and demand for spectrum, but rather inflated early award prices due to uncertainty about future awards. If so, that uncertainty has to some extent resolved. What we observe within noisy data as a downward trend in prices could simply be a step-change over the time period being considered that will not persist. Indeed, the trend could even reverse as demand for spectrum continues to increase with data traffic growth.

Given this, we do not see a strong case for applying the full extent of the trends shown in Table 2 to licences starting in the near future. Indeed, given the uncertainty in measuring and interpreting historical price movements, a reasonable case could be made for assuming that real prices remain flat (i.e. increasing prices over time for inflation) in the absence of clear evidence for an alternative approach. The ACMA's current approach implicitly applies a decline in real prices at inflation expectations (2-3%) and so is a compromise between these positions.

*Econometric techniques*

Fuller examination of time movements in spectrum prices using richer models would be needed to reach firmer conclusions. In particular, the possibility of some earlier spectrum award prices being boosted by risks relating to future spectrum availability that have now resolved needs to be considered. At first sight, this appears to explain much of the observed differences in prices over time and does not imply sustained time trends in prices that can be extrapolated into the future. We also need to be careful that conclusions are not created by artifacts arising from the particular time period being considered. Any projection of prices into the future should ideally be tested through retaining some data for out-of-sample testing of model predictions. Such modelling is outside the scope of our current exercise.

# 6 Band groups and substitutability

For the purpose of the benchmarking analysis, the ACMA has split the relevant bands into four groups, with bands in each group considered sufficiently substitutable and likely to have similar value. These groups are:

- **Sub-1 GHz:** 700 MHz and 850 GHz
- **Lower 1-3 GHz:** 1800 MHz and 2 GHz
- **Upper 1-3 GHz:** 2.3 GHz and 2.5 GHz
- **3.4 GHz**: 3.4 – 3.7 GHz

*Grouping comparable bands*

The intention of the grouping is to, where appropriate, increase the number of (suitable) price observations used for the benchmarking when forming value estimates. For the purpose of this benchmarking exercise, the ACMA has also included observations in similar bands which are not up for renewal in Australia. This is in line with standard practice provided that significantly dissimilar spectrum is not grouped together.

The bands included in a group do not need to be perfect substitutes (and indeed are unlikely to be for all users, as network configurations and specific usage requirements in each band will differ). Nevertheless, where bands are grouped, they should be at least partial substitutes with reasonable expectations of having similar value to users within the sample period.

*Pooling unless evidence of price differences*

The reliability of price estimates will be increased by pooling observations where possible. There is particular benefit in pooling wherever possible given the limited amount of data and large variability in the achieved prices of similar spectrum across different auctions. Where spectrum is split into different groups, this should be based on evidence (ideally statistically significant evidence) of differences in prices.

Our view is that the groupings chosen by the ACMA are appropriate, as discussed below.

## Sub-1 GHz grouping

Sub-1 GHz bands are typically used as the coverage layer for mobile services, given their relatively favourable propagation characteristics (in terms of both coverage and in-building penetration). Consequently, these bands are generally more valuable to mobile operators than higher frequencies. This is clearly reflected in the benchmarking data. Therefore, sub-1 GHz spectrum needs to be considered separately to the other bands in the benchmarking.

However, we believe that the 700 MHz and 850 MHz bands can be reasonably grouped together for the benchmarking on account of the similar propagation characteristics and similar expected future use in Australia for supporting the 4G and 5G mobile networks.[21]

## 1–3 GHz bands grouping

The grouping of the higher frequency bands is more complicated and was more contentious amongst stakeholders.

*Partial substitutes*

The 1–3 GHz bands offer similar total bandwidth and are all currently used in Australia for 4G and 5G WBB services. That usage is expected to continue in the future, although some operators intend to use some of this spectrum for other services, such as private networks and LEOSat D2D (outside metropolitan areas). On this basis, the 1–3 GHz bands could arguably all be considered at least partial substitutes for one another on a forward-looking basis.

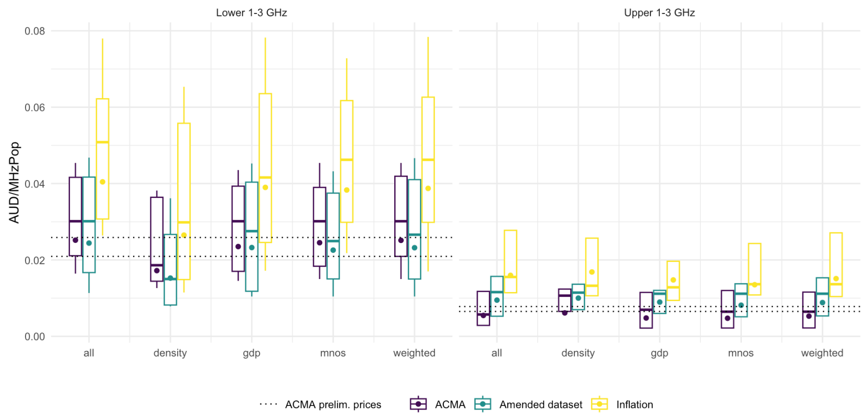
*Statistically significant price differences*

However, there are some differences across the bands (e.g. the 1800 MHz and 2 GHz bands have better propagation than the higher frequencies) and there are complicated timing issues with different bands awarded at different times and under different conditions. If these have led to significantly different prices in past auctions, it may therefore not be appropriate to group them all together for benchmarking purposes.

Figure 4 shows the distribution of the benchmarking results for the Lower 1 – 3 GHz and Upper 1 – 3 GHz groups. Visually there appears to be a structural difference in the data for the two groups.

[21] *Expiring spectrum licences, stage 3 Supporting paper 1: Overview of expiring spectrum licences, incumbent holdings, use and the secondary market*

*Figure 4: Benchmarking output for the Lower and Upper 1 - 3 GHz groups*




We ran Mann-Whitney U-tests to assess the statistical significance of differences in price observations for various band groupings. The results suggest that:

- There is a significant difference between observed prices for the Lower 1 – 3 GHz and the Upper 1-3 GHz groups used by the ACMA. Although the data suggests there is some convergence of prices across all four bands over time, the differences in observations over the period considered are still too great for the data for all four bands to be combined.
- There is no statistical difference between the data samples for the 1800 MHz, 1900 MHz and 2100 MHz bands. The Lower 1 – 3 GHz data does include some observations from 1500 MHz SDL awards, which have significantly lower prices than the other bands, so there may be some argument for removing those from the analysis.

There is an insufficient number of 2.3 GHz observations to run similar tests in relation to grouping the 2.3 GHz and 2.5 GHz bands with any degree of confidence. The median price for 2.3 GHz observations is above the median in the 2.5 GHz band, but all 2.3 GHz observations fall within the range of 2.5 GHz prices in the data and are well below median prices in the Lower 1-3 GHz bands. The 2.3 GHz band is configured for TDD, which is more flexible and therefore potentially more valuable than FDD spectrum (we discuss the implications of the 2.5 GHz FDD configuration below) – if anything, this points to the value of 2.3 GHz spectrum currently being potentially greater than the value of 2.5 GHz, but we have no strong evidence of whether this difference is significant.[22] Given the similar propagation characteristics and use cases of the bands, combined with a lack of clear evidence for treating them differently, we expect that *a priori* they can be grouped together.

*Upper vs Lower 1-3 GHz split*

On the basis of the above assessment, we believe the ACMA's split of the 1–3 GHz bands to be appropriate and supported by formal statistical testing of the data. However, as we noted above, this represents the historical situation over the period of the data set and there is also evidence of diminishing differences in prices between the Upper and Lower 1-3 GHz bands.

## Combining 3.4 GHz with Upper 1 – 3 GHz

The ACMA received comments during the consultation process that suggested the 3.4 GHz band should be included in the same group as the Upper 1 – 3 GHz bands. In particular, TPG argues the case on the grounds that:

- the 2.3 GHz and 3.4 GHz bands are substitutable; and
- the benchmarks for 3.4 GHz are significantly higher than for the Upper 1 – 3 GHz group because the ACMA has over-interpreted differences in prices paid in auctions without accounting for context in those markets.

Whilst we agree that there will be (imperfect) substitutability between the bands, this in itself is not sufficient currently to include the Upper 1–3 GHz bands and the 3.4 GHz band in the same group for the benchmarking.

*Particular characteristics of 3.4 GHz*

There are a variety of reasons why 3.4 GHz is (at least historically) different to the other bands and might need to be treated separately. The 3.4 GHz band is a pioneer band for 5G and is the main band used for 5G provision in Australia, although some operators are deploying 5G in other frequencies in the sub-1 GHz and 1 – 3 GHz bands. The 3.4 GHz band offers much larger (contiguous) bandwidth within spectrum holdings

[22] We have not identified any 2.3 GHz observations to add to the ACMA's sample, either using the detailed information provided by Telstra or our own SAD. However, NBN contends that there are examples of 2.3 GHz awards producing lower prices than 2.5 GHz awards within a country. It is difficult to confirm details of these additional awards without knowing the year that they occurred, but we suspect they may be pre-2013 awards and/or awards of residual spectrum. We do not see any need to change the overarching methodology to include these simply because they took place in the same country as other observations.

than the lower frequency bands as well as much better propagation compared to higher frequencies identified for 5G (i.e. the mmWave bands). Arguably, it is in a sweet spot between capacity and propagation that is not offered by the frequency ranges above and below.

Moreover, in several countries (particularly those with low population density) the 3.4 GHz band has historically been important for Wireless Local Loop (WLL). There is some evidence of higher average prices for 3.4 GHz spectrum in countries with lower population density due to the greater demand for this band for WLL applications.

*Statistical testing of differences between 3,4 GHz and Upper 1-3 GHz*

We ran Mann Whitney U tests on the samples included for the Upper 1-3 GHz group and the 3.4 GHz band to assess whether they could reasonably be combined. When using only the set of awards included by the ACMA in its original benchmarking, the tests indicate that the Upper 1 – 3 GHz data and the 3.4 GHz data are structurally different. On this basis, the decision of the ACMA to treat the 3.4 GHz band separately was justified.

However, repeating the tests on the larger dataset following the addition of more awards gives less conclusive results:

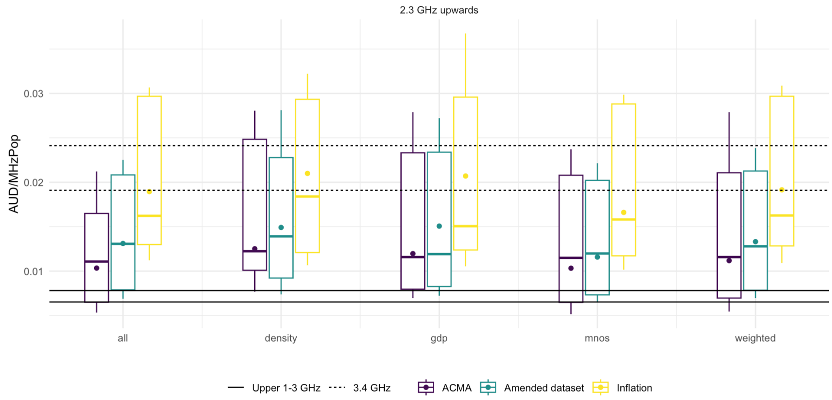
- if running the tests on MSR adjusted prices, the results continue to indicate that the samples are significantly different; but
- if running the tests on nominal or real prices, the difference is not statistically significant.

Broadly speaking the reason that enlarging the dataset reduces this difference is because the additions increase the median price for Upper 1-3 GHz, but lower the median price for 3.4 GHz, reducing the gap. Furthermore, the additional data increases uncertainty about 3.4 GHz prices, making it statistically less likely to find a difference.

*Potential for pooling bands suggested by enlarged dataset*

There is, therefore, some evidence that the Upper 1-3 GHz and 3.4 GHz bands could *potentially* be pooled on the basis of our enlarged dataset. Figure 5 below presents the range of pooled prices. After pooling, the median prices fall between the two provisional price ranges for the separate band groups. The interquartile range for the pooled data overlaps with only the 3.4 GHz proposed range. Put simply, the pooled estimates move up to reflect the 3.4 GHz prices, but there is a relatively high degree of uncertainty associated with these.

*Figure 5: Combined price range for Upper 1-3 GHz and 3.4 GHz observations*




*Maintaining separate groups*

Given the fragility of these statistical tests for differences, we do not see any difficulty with keeping them separate (as the ACMA has done), in particular given there are good *a priori* reasons why 3.4 GHz might need to be considered separately. There is also sufficient data available for assessing 3.4 GHz independently without the need to increase the sample size by pooling.

*Implications of 2.6 GHz FDD band plan*

The majority of the Upper 1-3 GHz observations are from the 2.6 GHz band, which is typically configured for FDD use, with TDD spectrum available in the 2.6 GHz duplex gap. The 3.4 GHz band, on the other hand, offers a large amount of TDD spectrum, which is more flexible as it can support different uplink/downlink profiles, making it more valuable in data heavy environments where downlink traffic exceeds uplink traffic. We note that there is a now a general preference for awarding spectrum in a TDD configuration and the 2.6 GHz FDD band plan is arguably there for historical reasons, rather than being the best way to use this spectrum. This likely depresses the current value of the 2.6 GHz band relative to 3.4 GHz. Hypothetically, rationalisation of the 2.6 GHz band plan could remove this difference, with the only remaining difference being modest propagation differences.

*Forward-looking vs historical considerations*

We do not agree that splitting the Upper 1-3 GHz and 3.4 GHz bands means that the ACMA would be putting "*statistical methodology choices above the legislative and MPS considerations*"[23], as claimed by TPG. The outcome of the benchmarking should not constrain the ACMA in its ability to take account of other relevant factors when making policy decisions on spectrum fees; benchmarking simply provides

[23] TPG response to the ACMA in relation to the Expiring Spectrum Licences Stage 3 consultation.

historical evidence to inform the overall exercise. In considering historical data, statistical analysis itself should still be conducted appropriately and in line with best practice. On this basis, the ACMA were fully justified to split out two groups given their original dataset. Our revisions suggest that there may some case for pooling, but in any case these revisions would lessen the gap between the Upper 1-3 GHz and 3.4 GHz bands even without pooling. If it was felt that greater emphasis should be given to forward looking considerations – primarily the potential for 2.6 GHz to be more valuable if offered in TDD configuration – then there may be a case for pooling, but the effect would be to increase the proposed fees for Upper 1-3 GHz, rather than materially reduce those for 3.4 GHz.

# 7 Filtering methodologies

## 7.1 Cohort variables

The ACMA has attempted to select observations that are most relevant to the Australian context based on:

- population density;
- GDP per capita and
- the number of MNOs active.

Filters are defined based on cutoff points applied to the ratio of the value of the cohort variable above for the observation country to the value in Australia.

*Which variables are important?*

Countries with higher population density or greater GDP per capita are likely to have higher spectrum prices, but, *a priori*, the effect of the number of MNOs on spectrum value is ambiguous.

*The number of MNOs*

Each observation in the dataset has either 3 or 4 MNOs. There are several potential impacts from the difference in the number of MNOs on spectrum prices:

- A four-player market might feature more intense competition in downstream markets, leading to lower valuation for spectrum within the auction due to reduction of any supernormal returns earned in a three-player market;
- Competition for that spectrum within an auction would also be more intense with four MNOs, potentially increasing the auction price relative to that valuation;
- With more MNOs, there would be less spectrum available per operator, potentially raising network costs if there is a lower spectral efficiency (even though the number of customers served per MHz is likely to be similar);
- Given the length of typical licences, even in four-player markets there may be expectations held at the time of the award of subsequent consolidation to three players;
- Regardless of the number of MNOs within the market, asymmetries in spectrum holdings and market shares may affect the marginal value of additional spectrum to particular players and, hence, auction outcomes.

On balance, it is reasonable to expect higher spectrum valuations in three-player markets relative to four-player markets, based on weaker downstream competition and possible spectral efficiency benefits from holding larger blocks of contiguous frequencies. However, incentives to compete at the margin for additional spectrum will also be much weaker in an auction with only three established players and no challengers.

Stakeholders have pointed out that even defining the number of MNOs in some countries is difficult. In Canada, for example, there are three national operators, but two of these are engaged in a comprehensive network sharing arrangement, leaving only two national networks. There are several regional incumbents who are strong competitors within their respective territories, as well as a handful of small local players.

The MNO cohort does not directly affect any of the price ranges proposed by the ACMA. This can be seen in Table 3 below in which we list the price ranges for each band group alongside the cohort that determines that price point.[24] Given this, the points raised by stakeholders on the number of MNOs in the US or Canada are largely inconsequential. We recommend simply removing the MNO filter from the analysis.

*GDP*

GDP per capita is relevant to spectrum values as operators expect to be able to achieve higher ARPU in higher income markets. However, using PPP rates partially corrects for income differences already and greatly diminishes the effect of GDP relative to using spot exchange rates. This can be seen in Table 3 below as the GDP filter sets the price points at the upper end of the range (which use spot rates) but not the price points at the lower end of the range (which use PPP rates).

As above, we recommend using PPP rates and therefore while GDP filtering is reasonable, it is of relatively low impact to the eventual results. In this context, we are neutral as to whether the ACMA applies GDP filtering. In practice it makes little difference and the ACMA may reasonably consider removing it from the analysis. However, we also see no problems with running the GDP filter as a verification step.

*Population density*

In our view, population density is the most important cohort variable in principle. However, as discussed above, it is difficult to establish the relevant value for population density in Australia given that geographic areas which will never be

[24] The upper and lower ends of the intersected price ranges will always correspond to the upper or lower end of a particular cohort or the weighted sample, which is the binding case or price setting. The ranges from the other cohorts are contained within the intersection, such that small changes to the price range for observations in e.g. the MNO cohort would not affect the final proposed prices at all.

covered by terrestrial networks within any reasonable timescale should be excluded. In addition, given that Australia's headline population density is by far the lowest in the dataset, any filtering should be done with caution. There is a danger of excluding data on the basis of measured population density differences that potentially overstate the relevant differences for mobile deployment focussed on populated areas. Rapid progress with deployment of satellite systems, especially 'base station in the air' solutions, reinforces the importance of not overstating the relevance of large unpopulated areas.

*Other filters*

We do not see a need to include any other filtering variables. There are, of course, all manner of factors that might affect spectrum valuations to some extent, but it is not feasible to collect comprehensive data on all of these or conduct robust analysis with many variables and relatively few observations.

Under the ACMA's cohort intersection methodology, it is also infeasible to keep adding cohorts and still have any non-empty price range without arbitrarily widening the percentile ranges, unless the price ranges for the additional cohorts are subsets of the existing price range intersection, in which case the additional variables make no difference.

## 7.2 Weighting methodology

The ACMA also defines a weighting methodology that assigns an average deviation of the three cohort variables (population density, GDP and number of MNOs) from their Australian values as its weight.

We find this weighting methodology difficult to interpret and believe it is largely unnecessary. It implies that GDP per capita, population density and the number of MNOs can be traded off against each other *one-for-one* (when measured as a proportion of the Australian value), which is arbitrary and difficult to justify.

The weighting methodology avoids choosing sharp cutoffs for the cohort variables, either side of which otherwise similar data is deemed relevant or irrelevant. We agree that it is helpful to avoid arbitrary choices where possible. However, this aim can be achieved more simply by including data whenever possible and only excluding observations if there is a clear case to do so. Weighting tends to bring the estimated price ranges back into line with what would be seen if the ACMA simply included all observations.

In our view, the analysis would be easier to follow and better justified if, as a starting point, the ACMA included all observations on an unweighted basis. Of the three filters used, population density is by far the most important, with GDP largely corrected by PPP rates and number of MNOs having unclear effects. Therefore, we clearly need to check the impact of the population density filter, which as we have seen varies by band group. Then we may need to consider restricting to more recent observations if there are trends in real prices. This three-step approach is in line with general statistical practice to include all data unless there is a strong *a priori* reason or clear evidence to exclude it.

## 7.3 Estimate ranges

*Definition of ranges*

For each band group, the ACMA defines custom percentile ranges, which in most cases are narrower than the interquartile range. This means that prices more commonly fall outside of the range than inside it.

It then takes intersections of these ranges first between the various cohort groups and finally between PPP and spot versions of the data to arrive at a final price range. The lower end of this range is always set by the PPP exchange rate, while the upper end of the is always set by the spot exchange rate prices.

*Table 3: ACMA provisional price ranges*

| | Binding case | | Benchmark range | |
|---|---|---|---|---|
| Bands | Lower | Upper | Lower | Upper |
| Sub-1 GHz | weighted-ppp | gdp-spot | 0.0690 | 0.0844 |
| Lower 1-3 GHz | weighted-ppp | gdp-spot | 0.0209 | 0.0259 |
| Upper 1-3 GHz | density-ppp | density-spot | 0.0065 | 0.0078 |
| 3.4 GHz | density-ppp | density-spot | 0.0191 | 0.0241 |

*Central tendency and dispersion*

This approach narrows the price range and means that the recommended ranges do not represent typical measures of the uncertainty around spectrum prices. Therefore, we interpret the provisional ranges to be something between a measure of central tendency (the median) and a commonly-used measure of dispersion (the interquartile range). Therefore, the provisional ranges are doing double duty, being neither a good measure of dispersion, nor the best indicator of central tendency.

Of course, it is eventually necessary to narrow this down to a single price, but in our view, it would be more interpretable to report a central estimate for value of spectrum alongside the interquartile range. This would allow more consistent treatment of the band groups and, being standard, widely used statistical measures, would be more interpretable than using non-standard percentile ranges. For the central estimate, the median is more appropriate to consider than a simple average (i.e. the arithmetic mean) given the highly skewed price data. However, the geometric mean could also be used on account of the logarithms of prices having close to a Normal distribution.

*Setting a single price*

This central estimate should be the starting point when deciding where to set the single price to apply to spectrum renewals. The ACMA should then consider whether there are any policy objectives or other factors affecting the value of spectrum that cannot be captured by the benchmarking analysis that might justify setting the price above or below the median. For example, the ACMA might have a strong expectation of convergence in prices in the bands above 1 GHz. If not, prices could simply be set at the median from the benchmarking analysis for all observations from 2018 onwards.

If other considerations are important, the ACMA would then have to apply discretion around where to set final prices, but this could reasonably be based on and supported by the data e.g. the lower/greater (depending on the nature of the desired adjustment) of the median and geometric mean, rather than directly taking the median. There is unlikely to be any case for setting the final price outside of the interquartile range.

*Intersecting ranges*

We see no case to take intersections of the ranges either between the cohorts or across PPP and spot exchange rates. If anything, uncertainty over the appropriate set of observations or exchange rate methodology might suggest taking the union of different price ranges.[25] However, it is best to pick a preferred measure (e.g. use all observations and PPP rates) and use other cuts of the data for sensitivity analysis.

We consider the intersecting of PPP and spot rate ranges to be more problematic than intersecting cohorts. In particular, considering the effect of population density (and to some extent GDP per capita) on spectrum prices is reasonable, even though it is difficult to do accurately, as discussed above. We

[25] The union of a set of price ranges is the range such that each point in the range falls inside at least one of the original price ranges (as opposed to all of the price ranges in the intersection).

can interpret the ACMA's proposed price ranges as reflecting its views on how density and GDP per capita affect prices. Where they are contained within the interquartile ranges of real prices in the amended dataset, we think it is reasonable for the ACMA to set a price within these ranges that is closest to the central estimates.

## 7.4 Amended results

In Figure 6 and Figure 7 we show further boxplots, first for all observations, then for each of the cohorts used by the ACMA. The boxplots can be read as above, with the only change being that groups of boxes are presented for *all observations*, then the three cohorts and finally the weighted sample.[26]

*Overlapping IQRs for filters*

The IQRs are much wider than the proposed price ranges and there is significant overlap between the IQRs for different cohorts. The median and geometric means of prices sit in or near the ACMA's proposed price ranges for the sub-1 GHz and 3.4-3.7 GHz bands, whereas the real prices for the 1-3 GHz bands are above the proposed price ranges. Awards of 1-3 GHz spectrum tend to have taken place earlier than awards in the other bands, and the difference between inflation-adjusted and MSR index values is greater for older awards (i.e. CPI has risen over time, the MSR index has fallen). Therefore, moving to real prices has a greater impact on prices in older awards, and therefore the estimated price ranges in the 1-3 GHz bands.

*Figure 6: Price ranges by cohort*

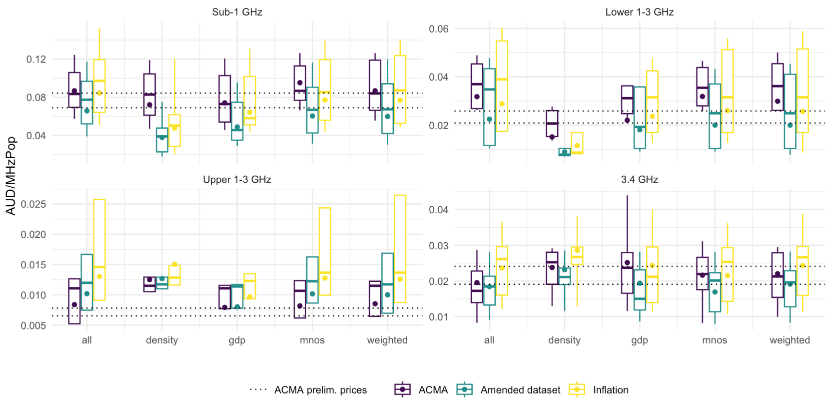

[26] We do not have reliable data for the number of MNOs in some of our observations. Given that we do not see a need for this filter, because of its limited effect both in theory and in the original ACMA data, we simply set missing MNO values to three, matching the number in Australia.

*Restricting to more recent benchmarks*

In Section 4 above, we noted that the prices in some bands have fallen over time and that the appropriate means for addressing this would be to filter out older observations. Therefore, we also present the same price ranges calculated only using observations from 2018 onwards. This leaves slightly more than half of the observations of the amended dataset[27] in all bands except the 3.4 GHz band, where the majority of awards were after this date.

Using only these later awards brings real PPP adjusted prices in the Lower 1-3 GHz band closer to the ACMA's provisional price ranges, although median prices remain slightly above. The provisional range for the Upper 1-3 GHz prices remains below the IQR of real prices.

*Figure 7: Price ranges by cohort - observations from 2018 onwards*




[27] There are 118 observations from 2018 onwards in the amended dataset, compared with 114 observations in total (i.e. from 2013 onwards) in the original dataset collated by the ACMA.

# 8 Conclusions

*Key changes*

We have added observations to ACMA's dataset and applied a simpler methodology based on:

- using PPP exchange rates and real prices;
- focusing the entire dataset, rather than filtering;
- using central price estimates (median or geometric mean) with the inter-quartile range as a measure of dispersion.

The ACMA's provisional price ranges are difficult to interpret because they do not explicitly distinguish between central estimates and measures of spread, being based on percentiles inside the interquartile range and intersection of ranges obtained under PPP and spot exchange rates.

There are two subsets of data that are also worth consideration as a cross-check:

- filtering by population density given the exceptionally low population density in Australia (though noting that headline figures do not allow for geographical areas that will not be covered);
- considering a subset of later observations from 2018 onwards to control for any changes in spectrum value over time.

*Our analysis supports ACMA provisional ranges*

This simpler analysis is broadly supportive of ACMA's provisional ranges, as shown in Figure 6 above. However, the extent of uncertainty about prices is greater than suggested by the ACMA's ranges given how these have been derived. We consider that interquartile ranges (as shown by whiskers in Figure 6) more properly represent this uncertainty, as they show where half of observations fall.

*Sub 1-GHz*

Looking first at the Sub 1-GHz band according to our methodology:

- Looking at all observations, the median is approximately at the upper end of the ACMA's provisional range, which itself falls into the IQR (see Figure 6). This suggests that ACMA's provisional range is reasonable. Restricting to more recent observations only (Figure 7) does not change this conclusion.
- Restricting to low population density benchmarks lowers the median (on all data using our methodology – see Figure 7) to approximately the lower end of ACMA's range, though the whole range is still within the IQR;

- Both restricting to low population density and taking more recent observations pushes our median below the ACMA's provisional range. However, the ACMA's range is not contraindicated as it is still within the IQR and we have many fewer observations with both filters applied. Therefore, we do not consider that this is sufficient evidence by itself to set a lower price for Sub-1 GHz.

These results suggest that the upper end of ACMA's range may be more appropriate for the Sub-1 GHz band, though this somewhat depends on what coverage obligations might be associated with licences.

*Lower 1-3 GHz*

For the Lower 1-3 GHz band:

- With all observations included, we obtain a higher price than ACMA provisional range, with our IQR above this range;
- This difference is much reduced by restricting observations to low population density cases, with our median then falling at the top of the ACMA provision range;
- Restricting to more recent observations also lowers our median, which is then above, but close to the top of the ACMA's provisional range;
- Both restricting to low population density cases and more recent observations pushes our median below the ACMA range, but we have few observations.

Therefore, there is some weak evidence that the ACMA range for Lower 1-3 GHz could be increased, but this evidence is not particularly robust once we look at filtered data. Overall, the top end of the ACMA range appears favoured.

*Upper 1-3 GHz band*

For the Upper 1-3 GHz bands, we believe the ACMA's proposed price range is too low and this should be closer to the proposed prices for the Lower 1-3 GHz bands or 3.4 GHz band.

Looking at Figure 6, the IQR from our analysis lies above the ACMA's proposed range for the whole data set and when filtering to low population density case only. Looking at Figure 7, the situation on restricting to later data since 2018 is similar. However, there is some small overlap with the ACMA's range in the case that we do not filter by population density, but our median is still well above the range. We conclude that there is reasonable evidence here that the proposed prices for the Upper 1-3 GHz band should be higher.

The difference between Upper 1-3 GHz bands and these other two bands is likely overstated by the ACMA provisional ranges and there would be some case for pooling the bands, although there are enough observations in each group that this is not necessary and instead we consider the mode of use of the two groups. As discussed above, what appears to be happening is that the Upper 1-3 GHz results are strongly driven by 2.6 GHz band awards where an FDD band plan was in use. More recent awards above 1 GHz, especially in 3.4 GHz, use a TDD band plan that provides more flexibility to accommodate asymmetric uplink/downlink traffic. Whilst the value of spectrum in the 1-3 GHz range is converging, this convergence has not yet run to completion and arguably the value of 2.6 GHz spectrum is somewhat impaired by its historic band plan. Whilst there is a reasonable case to treat these bands on a similar basis *if looking forward*, benchmark data looks backwards and there is still some difference. Therefore, although there is an arguable case for pooling, this is probably somewhat premature.

Given this, we would suggest that the ACMA consider revising its provisional prices for the Upper 1-3 GHz band up, closer to the other supra-1 GHz bands, but not necessarily equal to their prices.

*3.4 GHz*

The ACMA's provisional range for 3.4 GHz is supported by our analysis in that:

- Taking all observations (in Figure 6), the geometric mean is at the lower end of ACMA's range and the median is slightly below;
- Restricting the dataset to low population density cases places the geometric mean in the centre of the range with the median slightly above, as does taking more recent observations only;
- Both restricting the dataset to low population density cases and more recent observations places the median above, but close to the upper end of ACMA's provision range; and
- In all four cases, the ACMA's range falls within our IQR.

Our analysis does not indicate any particular preference for either end of the range, suggesting the midpoint may be a reasonable choice of a single price point. If strong demand for WLL applications is expected for 3.4 GHz spectrum, the upper end of the range might be more appropriate.

We note that the benchmarking puts 3.4 GHz values higher than the value of the Upper 1 -3 GHz bands. Broadly speaking we might expect the value of spectrum to fall as the frequency increases, due to inferior propagation characteristics in the higher bands. However, there are other drivers of spectrum licence value, some of which may be transient (e.g. short-term lack of substitutable spectrum) while others may be more persistent (e.g. specific characteristics of the band, configuration of the band plan). As discussed earlier, the 3.4 GHz band falls in a sweet spot for 5G, with greater bandwidths available than in the lower frequencies but with reasonable (although somewhat inferior) propagation. It is also available in a TDD arrangement. The Upper 1-3 GHz value estimates are largely driven by 2.5 GHz awards, where value might be somewhat depressed by the historic choice to make the band primarily available for FDD licences. Therefore, whilst it is very difficult to know precisely how valuations will change in the future, we do not believe that 3.4 GHz benchmarks being higher than the Upper 1-3 GHz benchmarks provides good evidence that the 3.4 GHz band would be overpriced with fees set in the range established by the ACMA. On the contrary, as discussed above there is evidence to suggest that the proposed price range for the Upper 1-3 GHz might be too low.

# Annex A Additional awards

The following table lists the awards we have added to the ACMA data for our analysis. It includes both awards suggested by stakeholders and others found using our SAD.

*Table 4: Additional awards*

| Country | Band | Year |
|---|---|---|
| Canada | 700 MHz | 2014 |
| New Zealand | 700 MHz | 2014 |
| France | 700 MHz | 2015 |
| Germany | 700 MHz | 2015 |
| Finland | 700 MHz | 2016 |
| Norway | 700 MHz | 2019 |
| Austria | 700 MHz | 2020 |
| Hungary | 700 MHz | 2020 |
| Netherlands | 700 MHz | 2020 |
| Chile | 700 MHz | 2021 |
| Latvia | 700 MHz | 2021 |
| Czech Republic | 800 MHz | 2013 |
| Finland | 800 MHz | 2013 |
| Lithuania | 800 MHz | 2013 |
| United Kingdom | 800 MHz | 2013 |
| Poland | 800 MHz | 2015 |
| Iceland | 800 MHz | 2023 |
| Germany | 900 MHz | 2015 |
| Iceland | 900 MHz | 2023 |

| | | |
|---|---|---|
| Austria | 1500 MHz | 2020 |
| Netherlands | 1500 MHz | 2020 |
| Denmark | 1500 MHz | 2021 |
| Belgium | 1500 MHz | 2022 |
| Latvia | 1500 MHz | 2022 |
| Costa Rica | 1700 MHz | 2017 |
| Chile | 1700 MHz | 2021 |
| Norway | 1800 MHz | 2016 |
| Costa Rica | 1800 MHz | 2017 |
| Greece | 1800 MHz | 2017 |
| New Zealand | 1800 MHz | 2019 |
| Iceland | 1800 MHz | 2023 |
| Iceland | 2100 MHz | 2017 |
| Hungary | 2100 MHz | 2018 |
| New Zealand | 2100 MHz | 2019 |
| Norway | 2100 MHz | 2019 |
| Austria | 2100 MHz | 2020 |
| Netherlands | 2100 MHz | 2020 |
| Singapore | 2100 MHz | 2021 |
| Iceland | 2100 MHz | 2023 |
| Spain | 2600 MHz | 2016 |
| Iceland | 2600 MHz | 2017 |
| Mexico | 2600 MHz | 2018 |
| Mexico | 2600 MHz | 2018 |
| Spain | 3500 MHz | 2016 |

| | | |
|---|---|---|
| Czech Republic | 3500 MHz | 2017 |
| Latvia | 3500 MHz | 2017 |
| Latvia | 3500 MHz | 2018 |
| Czech Republic | 3500 MHz | 2020 |
| Hungary | 3500 MHz | 2020 |
| Singapore | 3500 MHz | 2020 |
| Chile | 3500 MHz | 2021 |
| Sweden | 3500 MHz | 2021 |
| Iceland | 3500 MHz | 2023 |
| Croatia | 3500 MHz | 2023 |
| Netherlands | 3500 MHz | 2024 |
| Austria | 3500 MHz | 2024 |
| Germany | 3700 MHz | 2019 |
| United Kingdom | 3700 MHz | 2021 |

# Annex B Results of statistical tests

Above, we refer to several statistical tests we have used to assess differences between prices in different band groups or different time periods. In this annex, we present the detailed results of these tests in tables of p values. We have used a significance level of 5%, so we say there is a significant difference in prices when the values in the table are less than 0.05.

In addition to the Mann Whitney-U tests, we ran t-tests on differences in log prices as a robustness check. Results were similar across the two test types.

*Table 5: Band grouping statistical test results – p-values*

| | | MSR | | Nominal | | Real | |
|---|---|---|---|---|---|---|---|
| #Obs. | Band groups | MW | t | MW | t | MW | t |
| All | | | | | | | |
| 76 | Lower 1-3 GHz/Upper 1-3 GHz | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 72 | 3.4 GHz/Upper 1-3 GHz | 0.021 | 0.023 | 0.163 | 0.110 | 0.201 | 0.145 |
| 98 | Lower 1-3 GHz/3.4 GHz | 0.005 | 0.020 | 0.000 | 0.002 | 0.000 | 0.002 |
| ACMA only | | | | | | | |
| 52 | Lower 1-3 GHz/Upper 1-3 GHz | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 52 | 3.4 GHz/Upper 1-3 GHz | 0.001 | 0.001 | 0.018 | 0.009 | 0.018 | 0.010 |
| 62 | Lower 1-3 GHz/3.4 GHz | 0.029 | 0.117 | 0.004 | 0.010 | 0.002 | 0.008 |
| Density filter | | | | | | | |
| 29 | Lower 1-3 GHz/Upper 1-3 GHz | 0.130 | 0.130 | 0.151 | 0.126 | 0.140 | 0.131 |
| 27 | 3.4 GHz/Upper 1-3 GHz | 0.085 | 0.089 | 0.143 | 0.180 | 0.222 | 0.217 |
| 36 | Lower 1-3 GHz/3.4 GHz | 0.705 | 0.695 | 0.462 | 0.467 | 0.329 | 0.406 |

*Note: Band grouping A/B row tests whether prices in group A are significantly greater than prices in group B. Tests conducted separately on MSR adjusted, nominal and real prices.*

For the bands within the Lower 1-3 GHz group, we tested whether prices in that particular band were significantly different to prices in the rest of the group. The only significant difference was between 1500 MHz prices and the other bands.

*Table 6: Bands in the Lower 1-3 GHz group statistical tests - p-values*

| | MSR | | Nominal | | Real | |
|---|---|---|---|---|---|---|
| Band | MW | t | MW | t | MW | t |
| 1500 MHz | 0.027 | 0.036 | 0.019 | 0.034 | 0.013 | 0.032 |
| 1800 MHz | 0.363 | 0.259 | 0.219 | 0.173 | 0.165 | 0.136 |
| 1900 MHz | 0.395 | 0.320 | 0.091 | 0.135 | 0.063 | 0.118 |
| 2100 MHz | 0.720 | 0.692 | 0.388 | 0.430 | 0.315 | 0.374 |

We then tested whether prices in each band group were significantly different in different time periods.

*Table 7: Differences in prices pre-2018 compared with 2018 onwards - p-values*

| | | MSR | | Nominal | | Real | |
|---|---|---|---|---|---|---|---|
| Band groups | #Obs. | MW | t | MW | t | MW | t |
| Sub-1 GHz | 49 | 0.882 | 0.815 | 0.233 | 0.142 | 0.144 | 0.102 |
| Lower 1-3 GHz | 51 | 0.428 | 0.314 | 0.020 | 0.030 | 0.009 | 0.020 |
| Upper 1-3 GHz | 25 | 0.736 | 0.385 | 0.283 | 0.118 | 0.183 | 0.103 |
| 3.4 GHz | 47 | 1.000 | 0.998 | 0.995 | 0.997 | 0.995 | 0.998 |

*Table 8: Differences in prices pre-2017 compared with 2021 onwards - p-values*

| | | MSR | | Nominal | | Real | |
|---|---|---|---|---|---|---|---|
| Band groups | #Obs. | MW | t | MW | t | MW | t |
| Sub-1 GHz | 29 | 0.903 | 0.907 | 0.249 | 0.200 | 0.162 | 0.168 |
| Lower 1-3 GHz | 27 | 0.452 | 0.342 | 0.022 | 0.030 | 0.011 | 0.022 |
| Upper 1-3 GHz | 18 | 0.683 | 0.457 | 0.118 | 0.127 | 0.061 | 0.115 |

Finally, we re-ran the tests for differences in prices between band groups based on pre-2017 awards and separately for awards from 2021 onwards, to test convergence in prices between supra-1 GHz bands.

*Table 9: Differences in prices between band groups at different points in time - p-values*

| | | MSR | | Nominal | | Real | |
|---|---|---|---|---|---|---|---|
| #Obs. | Band groups | MW | t | MW | t | MW | t |
| First third | | | | | | | |
| 24 | Lower 1-3 GHz/Upper 1-3 GHz | 0.000 | 0.001 | 0.000 | 0.001 | 0.000 | 0.001 |
| Final third | | | | | | | |
| 23 | Lower 1-3 GHz/Upper 1-3 GHz | 0.014 | 0.002 | 0.008 | 0.002 | 0.024 | 0.003 |
| 36 | 3.4 GHz/Upper 1-3 GHz | 0.041 | 0.017 | 0.034 | 0.012 | 0.045 | 0.019 |
| 39 | Lower 1-3 GHz/3.4 GHz | 0.290 | 0.296 | 0.251 | 0.297 | 0.264 | 0.310 |

# Annex C Detailed results

In this annex we provide the data on price ranges and summary statistics presented in Figure 6 and Figure 7.

*Table 10: Data for Figure 6*

| Band group | Cohort | Data | #Obs | Q1 | Lower | Median | Upper | Q3 | Geometric mean |
|---|---|---|---|---|---|---|---|---|---|
| Sub-1 GHz | all | ACMA | 29 | 0.0556 | 0.0685 | 0.0840 | 0.1125 | 0.1262 | 0.0811 |
| Sub-1 GHz | density | ACMA | 9 | 0.0408 | 0.0456 | 0.0690 | 0.0901 | 0.1189 | 0.0545 |
| Sub-1 GHz | gdp | ACMA | 15 | 0.0444 | 0.0613 | 0.0829 | 0.1126 | 0.1225 | 0.0700 |
| Sub-1 GHz | mnos | ACMA | 18 | 0.0583 | 0.0689 | 0.0848 | 0.1122 | 0.1244 | 0.0785 |
| Sub-1 GHz | weighted | ACMA | 29 | 0.0550 | 0.0690 | 0.0840 | 0.1151 | 0.1262 | 0.0764 |
| Sub-1 GHz | all | Amended dataset | 49 | 0.0298 | 0.0404 | 0.0643 | 0.0889 | 0.1119 | 0.0582 |
| Sub-1 GHz | density | Amended dataset | 18 | 0.0182 | 0.0229 | 0.0389 | 0.0497 | 0.0658 | 0.0386 |
| Sub-1 GHz | gdp | Amended dataset | 28 | 0.0230 | 0.0330 | 0.0457 | 0.0683 | 0.1002 | 0.0490 |
| Sub-1 GHz | mnos | Amended dataset | 38 | 0.0230 | 0.0359 | 0.0559 | 0.0694 | 0.1033 | 0.0512 |
| Sub-1 GHz | weighted | Amended dataset | 49 | 0.0231 | 0.0389 | 0.0638 | 0.0840 | 0.1119 | 0.0546 |
| Sub-1 GHz | all | Inflation | 49 | 0.0519 | 0.0681 | 0.0978 | 0.1440 | 0.1908 | 0.0950 |
| Sub-1 GHz | density | Inflation | 18 | 0.0351 | 0.0483 | 0.0664 | 0.0884 | 0.1393 | 0.0653 |
| Sub-1 GHz | gdp | Inflation | 28 | 0.0495 | 0.0560 | 0.0883 | 0.1392 | 0.1747 | 0.0864 |
| Sub-1 GHz | mnos | Inflation | 38 | 0.0478 | 0.0633 | 0.0865 | 0.1390 | 0.1767 | 0.0875 |
| Sub-1 GHz | weighted | Inflation | 49 | 0.0488 | 0.0635 | 0.0972 | 0.1394 | 0.1936 | 0.0914 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Lower 1-3 GHz | all | ACMA | 37 | 0.0164 | 0.0211 | 0.0301 | 0.0416 | 0.0454 | 0.0252 |
| Lower 1-3 GHz | density | ACMA | 12 | 0.0126 | 0.0144 | 0.0186 | 0.0364 | 0.0382 | 0.0172 |
| Lower 1-3 GHz | gdp | ACMA | 15 | 0.0145 | 0.0170 | 0.0301 | 0.0393 | 0.0435 | 0.0235 |
| Lower 1-3 GHz | mnos | ACMA | 25 | 0.0150 | 0.0184 | 0.0301 | 0.0390 | 0.0454 | 0.0245 |
| Lower 1-3 GHz | weighted | ACMA | 37 | 0.0150 | 0.0209 | 0.0301 | 0.0419 | 0.0454 | 0.0251 |
| Lower 1-3 GHz | all | Amended dataset | 51 | 0.0113 | 0.0167 | 0.0301 | 0.0417 | 0.0468 | 0.0244 |
| Lower 1-3 GHz | density | Amended dataset | 19 | 0.0079 | 0.0082 | 0.0150 | 0.0267 | 0.0362 | 0.0152 |
| Lower 1-3 GHz | gdp | Amended dataset | 26 | 0.0104 | 0.0118 | 0.0275 | 0.0404 | 0.0453 | 0.0232 |
| Lower 1-3 GHz | mnos | Amended dataset | 43 | 0.0104 | 0.0150 | 0.0249 | 0.0375 | 0.0432 | 0.0226 |
| Lower 1-3 GHz | weighted | Amended dataset | 51 | 0.0104 | 0.0150 | 0.0266 | 0.0410 | 0.0467 | 0.0232 |
| Lower 1-3 GHz | all | Inflation | 51 | 0.0264 | 0.0307 | 0.0508 | 0.0622 | 0.0780 | 0.0405 |
| Lower 1-3 GHz | density | Inflation | 19 | 0.0115 | 0.0149 | 0.0298 | 0.0558 | 0.0653 | 0.0265 |
| Lower 1-3 GHz | gdp | Inflation | 26 | 0.0172 | 0.0246 | 0.0416 | 0.0635 | 0.0782 | 0.0390 |
| Lower 1-3 GHz | mnos | Inflation | 43 | 0.0218 | 0.0299 | 0.0462 | 0.0617 | 0.0728 | 0.0383 |
| Lower 1-3 GHz | weighted | Inflation | 51 | 0.0170 | 0.0298 | 0.0462 | 0.0626 | 0.0784 | 0.0387 |
| Upper 1-3 GHz | all | ACMA | 29 | 0.0030 | 0.0029 | 0.0057 | 0.0118 | 0.0116 | 0.0055 |
| Upper 1-3 GHz | density | ACMA | 9 | 0.0070 | 0.0065 | 0.0107 | 0.0124 | 0.0122 | 0.0061 |
| Upper 1-3 GHz | gdp | ACMA | 13 | 0.0022 | 0.0022 | 0.0070 | 0.0115 | 0.0115 | 0.0048 |
| Upper 1-3 GHz | mnos | ACMA | 19 | 0.0022 | 0.0022 | 0.0064 | 0.0120 | 0.0119 | 0.0047 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Upper 1-3 GHz | weighted | ACMA | 29 | 0.0022 | 0.0022 | 0.0064 | 0.0116 | 0.0116 | 0.0053 |
| Upper 1-3 GHz | all | Amended dataset | 25 | 0.0053 | 0.0053 | 0.0116 | 0.0157 | 0.0153 | 0.0095 |
| Upper 1-3 GHz | density | Amended dataset | 10 | 0.0070 | 0.0070 | 0.0114 | 0.0136 | 0.0135 | 0.0100 |
| Upper 1-3 GHz | gdp | Amended dataset | 11 | 0.0062 | 0.0060 | 0.0112 | 0.0120 | 0.0120 | 0.0090 |
| Upper 1-3 GHz | mnos | Amended dataset | 19 | 0.0052 | 0.0051 | 0.0112 | 0.0138 | 0.0137 | 0.0081 |
| Upper 1-3 GHz | weighted | Amended dataset | 25 | 0.0053 | 0.0053 | 0.0112 | 0.0153 | 0.0139 | 0.0088 |
| Upper 1-3 GHz | all | Inflation | 25 | 0.0117 | 0.0114 | 0.0155 | 0.0278 | 0.0271 | 0.0160 |
| Upper 1-3 GHz | density | Inflation | 10 | 0.0107 | 0.0106 | 0.0132 | 0.0257 | 0.0249 | 0.0169 |
| Upper 1-3 GHz | gdp | Inflation | 11 | 0.0096 | 0.0094 | 0.0128 | 0.0197 | 0.0194 | 0.0148 |
| Upper 1-3 GHz | mnos | Inflation | 19 | 0.0111 | 0.0108 | 0.0137 | 0.0243 | 0.0227 | 0.0135 |
| Upper 1-3 GHz | weighted | Inflation | 25 | 0.0104 | 0.0104 | 0.0137 | 0.0271 | 0.0264 | 0.0151 |
| 3.4 GHz | all | ACMA | 29 | 0.0083 | 0.0140 | 0.0172 | 0.0228 | 0.0287 | 0.0195 |
| 3.4 GHz | density | ACMA | 10 | 0.0130 | 0.0191 | 0.0253 | 0.0281 | 0.0292 | 0.0238 |
| 3.4 GHz | gdp | ACMA | 16 | 0.0116 | 0.0166 | 0.0237 | 0.0279 | 0.0440 | 0.0252 |
| 3.4 GHz | mnos | ACMA | 20 | 0.0082 | 0.0176 | 0.0219 | 0.0266 | 0.0311 | 0.0216 |
| 3.4 GHz | weighted | ACMA | 29 | 0.0100 | 0.0154 | 0.0213 | 0.0279 | 0.0295 | 0.0220 |
| 3.4 GHz | all | Amended dataset | 47 | 0.0079 | 0.0121 | 0.0161 | 0.0209 | 0.0264 | 0.0156 |
| 3.4 GHz | density | Amended dataset | 17 | 0.0083 | 0.0164 | 0.0208 | 0.0225 | 0.0282 | 0.0188 |
| 3.4 GHz | gdp | Amended dataset | 27 | 0.0082 | 0.0114 | 0.0128 | 0.0226 | 0.0281 | 0.0186 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3.4 GHz | mnos | Amended dataset | 35 | 0.0072 | 0.0102 | 0.0154 | 0.0214 | 0.0264 | 0.0140 |
| 3.4 GHz | weighted | Amended dataset | 47 | 0.0079 | 0.0121 | 0.0172 | 0.0214 | 0.0282 | 0.0164 |
| 3.4 GHz | all | Inflation | 47 | 0.0111 | 0.0141 | 0.0202 | 0.0280 | 0.0350 | 0.0208 |
| 3.4 GHz | density | Inflation | 17 | 0.0109 | 0.0186 | 0.0266 | 0.0288 | 0.0347 | 0.0239 |
| 3.4 GHz | gdp | Inflation | 27 | 0.0117 | 0.0135 | 0.0163 | 0.0291 | 0.0396 | 0.0238 |
| 3.4 GHz | mnos | Inflation | 35 | 0.0099 | 0.0132 | 0.0163 | 0.0277 | 0.0350 | 0.0186 |
| 3.4 GHz | weighted | Inflation | 47 | 0.0109 | 0.0141 | 0.0240 | 0.0295 | 0.0377 | 0.0216 |

*Table 11: Data for Figure 7*

| Band group | Cohort | Data | #Obs | Q1 | Lower | Median | Upper | Q3 | Geometric mean |
|---|---|---|---|---|---|---|---|---|---|
| Sub-1 GHz | all | ACMA | 22 | 0.0574 | 0.0695 | 0.0834 | 0.1058 | 0.1244 | 0.0868 |
| Sub-1 GHz | density | ACMA | 5 | 0.0468 | 0.0612 | 0.0829 | 0.1045 | 0.1189 | 0.0721 |
| Sub-1 GHz | gdp | ACMA | 8 | 0.0456 | 0.0540 | 0.0729 | 0.1027 | 0.1207 | 0.0741 |
| Sub-1 GHz | mnos | ACMA | 13 | 0.0664 | 0.0769 | 0.0868 | 0.1128 | 0.1262 | 0.0952 |
| Sub-1 GHz | weighted | ACMA | 22 | 0.0556 | 0.0664 | 0.0840 | 0.1189 | 0.1262 | 0.0868 |
| Sub-1 GHz | all | Amended dataset | 31 | 0.0389 | 0.0522 | 0.0775 | 0.0967 | 0.1174 | 0.0658 |
| Sub-1 GHz | density | Amended dataset | 10 | 0.0180 | 0.0228 | 0.0389 | 0.0478 | 0.0752 | 0.0379 |
| Sub-1 GHz | gdp | Amended dataset | 14 | 0.0292 | 0.0351 | 0.0457 | 0.0748 | 0.0955 | 0.0489 |
| Sub-1 GHz | mnos | Amended dataset | 22 | 0.0314 | 0.0426 | 0.0669 | 0.0905 | 0.1164 | 0.0604 |
| Sub-1 GHz | weighted | Amended dataset | 31 | 0.0303 | 0.0421 | 0.0674 | 0.0941 | 0.1198 | 0.0599 |
| Sub-1 GHz | all | Inflation | 31 | 0.0510 | 0.0641 | 0.0972 | 0.1194 | 0.1527 | 0.0844 |
| Sub-1 GHz | density | Inflation | 10 | 0.0203 | 0.0286 | 0.0504 | 0.0617 | 0.1201 | 0.0477 |
| Sub-1 GHz | gdp | Inflation | 14 | 0.0438 | 0.0511 | 0.0581 | 0.1017 | 0.1310 | 0.0643 |
| Sub-1 GHz | mnos | Inflation | 22 | 0.0434 | 0.0559 | 0.0853 | 0.1194 | 0.1393 | 0.0771 |
| Sub-1 GHz | weighted | Inflation | 31 | 0.0488 | 0.0528 | 0.0872 | 0.1237 | 0.1394 | 0.0768 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Lower 1-3 GHz | all | ACMA | 14 | 0.0263 | 0.0269 | 0.0369 | 0.0453 | 0.0488 | 0.0318 |
| Lower 1-3 GHz | density | ACMA | 2 | 0.0137 | 0.0154 | 0.0207 | 0.0261 | 0.0277 | 0.0152 |
| Lower 1-3 GHz | gdp | ACMA | 4 | 0.0213 | 0.0248 | 0.0311 | 0.0363 | 0.0365 | 0.0221 |
| Lower 1-3 GHz | mnos | ACMA | 8 | 0.0258 | 0.0280 | 0.0355 | 0.0438 | 0.0466 | 0.0319 |
| Lower 1-3 GHz | weighted | ACMA | 14 | 0.0261 | 0.0261 | 0.0361 | 0.0454 | 0.0500 | 0.0299 |
| Lower 1-3 GHz | all | Amended dataset | 29 | 0.0104 | 0.0117 | 0.0348 | 0.0433 | 0.0477 | 0.0225 |
| Lower 1-3 GHz | density | Amended dataset | 9 | 0.0071 | 0.0075 | 0.0079 | 0.0104 | 0.0104 | 0.0090 |
| Lower 1-3 GHz | gdp | Amended dataset | 15 | 0.0091 | 0.0104 | 0.0193 | 0.0358 | 0.0361 | 0.0181 |
| Lower 1-3 GHz | mnos | Amended dataset | 23 | 0.0091 | 0.0104 | 0.0249 | 0.0370 | 0.0432 | 0.0200 |
| Lower 1-3 GHz | weighted | Amended dataset | 29 | 0.0079 | 0.0104 | 0.0249 | 0.0410 | 0.0454 | 0.0200 |
| Lower 1-3 GHz | all | Inflation | 29 | 0.0170 | 0.0175 | 0.0389 | 0.0548 | 0.0602 | 0.0289 |
| Lower 1-3 GHz | density | Inflation | 9 | 0.0082 | 0.0082 | 0.0087 | 0.0170 | 0.0170 | 0.0116 |
| Lower 1-3 GHz | gdp | Inflation | 15 | 0.0126 | 0.0170 | 0.0315 | 0.0424 | 0.0475 | 0.0237 |
| Lower 1-3 GHz | mnos | Inflation | 23 | 0.0129 | 0.0170 | 0.0315 | 0.0512 | 0.0559 | 0.0260 |
| Lower 1-3 GHz | weighted | Inflation | 29 | 0.0087 | 0.0170 | 0.0315 | 0.0515 | 0.0589 | 0.0257 |
| Upper 1-3 GHz | all | ACMA | 12 | 0.0056 | 0.0052 | 0.0111 | 0.0126 | 0.0125 | 0.0084 |
| Upper 1-3 GHz | density | ACMA | 5 | 0.0107 | 0.0105 | 0.0115 | 0.0129 | 0.0122 | 0.0125 |
| Upper 1-3 GHz | gdp | ACMA | 6 | 0.0079 | 0.0077 | 0.0111 | 0.0116 | 0.0116 | 0.0079 |
| Upper 1-3 GHz | mnos | ACMA | 9 | 0.0064 | 0.0062 | 0.0107 | 0.0123 | 0.0122 | 0.0082 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Upper 1-3 GHz | weighted | ACMA | 12 | 0.0064 | 0.0064 | 0.0115 | 0.0122 | 0.0122 | 0.0085 |
| Upper 1-3 GHz | all | Amended dataset | 14 | 0.0080 | 0.0075 | 0.0120 | 0.0167 | 0.0165 | 0.0102 |
| Upper 1-3 GHz | density | Amended dataset | 5 | 0.0112 | 0.0110 | 0.0117 | 0.0129 | 0.0122 | 0.0127 |
| Upper 1-3 GHz | gdp | Amended dataset | 6 | 0.0080 | 0.0078 | 0.0114 | 0.0117 | 0.0117 | 0.0080 |
| Upper 1-3 GHz | mnos | Amended dataset | 11 | 0.0091 | 0.0086 | 0.0122 | 0.0162 | 0.0161 | 0.0101 |
| Upper 1-3 GHz | weighted | Amended dataset | 14 | 0.0070 | 0.0070 | 0.0117 | 0.0169 | 0.0153 | 0.0100 |
| Upper 1-3 GHz | all | Inflation | 14 | 0.0095 | 0.0091 | 0.0146 | 0.0257 | 0.0250 | 0.0130 |
| Upper 1-3 GHz | density | Inflation | 5 | 0.0117 | 0.0116 | 0.0128 | 0.0148 | 0.0137 | 0.0150 |
| Upper 1-3 GHz | gdp | Inflation | 6 | 0.0095 | 0.0093 | 0.0123 | 0.0135 | 0.0134 | 0.0097 |
| Upper 1-3 GHz | mnos | Inflation | 11 | 0.0102 | 0.0099 | 0.0137 | 0.0243 | 0.0230 | 0.0128 |
| Upper 1-3 GHz | weighted | Inflation | 14 | 0.0087 | 0.0087 | 0.0137 | 0.0264 | 0.0205 | 0.0126 |
| 3.4 GHz | all | ACMA | 29 | 0.0083 | 0.0140 | 0.0172 | 0.0228 | 0.0287 | 0.0195 |
| 3.4 GHz | density | ACMA | 10 | 0.0130 | 0.0191 | 0.0253 | 0.0281 | 0.0292 | 0.0238 |
| 3.4 GHz | gdp | ACMA | 16 | 0.0116 | 0.0166 | 0.0237 | 0.0279 | 0.0440 | 0.0252 |
| 3.4 GHz | mnos | ACMA | 20 | 0.0082 | 0.0176 | 0.0219 | 0.0266 | 0.0311 | 0.0216 |
| 3.4 GHz | weighted | ACMA | 29 | 0.0100 | 0.0154 | 0.0213 | 0.0279 | 0.0295 | 0.0220 |
| 3.4 GHz | all | Amended dataset | 43 | 0.0090 | 0.0133 | 0.0185 | 0.0213 | 0.0281 | 0.0184 |
| 3.4 GHz | density | Amended dataset | 16 | 0.0117 | 0.0190 | 0.0211 | 0.0236 | 0.0285 | 0.0231 |
| 3.4 GHz | gdp | Amended dataset | 26 | 0.0087 | 0.0119 | 0.0150 | 0.0231 | 0.0282 | 0.0194 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3.4 GHz | mnos | Amended dataset | 32 | 0.0080 | 0.0114 | 0.0201 | 0.0223 | 0.0281 | 0.0169 |
| 3.4 GHz | weighted | Amended dataset | 43 | 0.0083 | 0.0128 | 0.0196 | 0.0229 | 0.0282 | 0.0191 |
| 3.4 GHz | all | Inflation | 43 | 0.0122 | 0.0161 | 0.0261 | 0.0296 | 0.0365 | 0.0236 |
| 3.4 GHz | density | Inflation | 16 | 0.0128 | 0.0246 | 0.0267 | 0.0295 | 0.0383 | 0.0286 |
| 3.4 GHz | gdp | Inflation | 26 | 0.0114 | 0.0140 | 0.0212 | 0.0295 | 0.0400 | 0.0244 |
| 3.4 GHz | mnos | Inflation | 32 | 0.0107 | 0.0143 | 0.0253 | 0.0293 | 0.0362 | 0.0215 |
| 3.4 GHz | weighted | Inflation | 43 | 0.0113 | 0.0160 | 0.0266 | 0.0297 | 0.0388 | 0.0243 |