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Valuing spectrum at mm wavelengths for cellular networks

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Abstract - This paper investigates the economic value of spectrum at mm wavelengths. The analysis uses four techniques to value spectrum, namely a benchmarking comparison, a discounted cash flow analysis, a real options approach and a deprivation method.

The methods to calculate spectrum value presented in this paper can be used for any spectrum band and in any country. However, to determine the value of mm wavelengths for cellular networks, we have used data from New Zealand, specifically for the existing 700 MHz LTE network and for a hypothetical 28 GHz LTE network. These models are based on geographic data, population, cellular traffic analysis and LTE network design from this country. The results from the modelling analysis show that the value of spectrum in this case is bounded by the low value presented by the deprivation valuation method and by the high value presented in the real options approach. All results show that as the demand for network capacity increases then mm wavelength spectrum becomes more valuable.

This work will be useful to both regulators and operators. To regulators it offers insights into the economic value of mm wavelength spectrum which helps set fees for spectrum licenses and to set reserve price and expected budgets for future spectrum auctions. To operators this paper offers insights into spectrum valuation techniques and presents data on the value of mm wavelengths for cellular networks.

I. Introduction

Determining the value of spectrum is very important for both spectrum regulators and cellular network operators. Spectrum regulators need to determine the economic value of spectrum to set reasonable reserve prices for spectrum auctions or to set accurate fees for spectrum licenses. Similarly, network operators need to determine the value of spectrum specifically for their own networks, so that they don't over value spectrum to be purchased at auctions or spectrum purchased via secondary trading.

The risks and reasons to value spectrum accurately are significant. If operators value spectrum too low they risk not acquiring necessary spectrum in a competitive market. If operators value spectrum too highly, and pay too much for spectrum, they become less profitable or risk defaulting on payments to regulators. If regulators value spectrum too highly they risk setting reserve prices too high and this situation may lead to no operator being willing to buy spectrum or operators defaulting on payments for spectrum. If regulators set the value of spectrum too low, they risk creating inefficiencies in spectrum use and allocation e.g. where operators buy spectrum and do not use it.

With the high demand for wireless traffic there is pressure for regulators to assign more spectrum for cellular networks. One answer to meet this demand for spectrum is to use mm wavelengths. Millimetre wavelengths are defined as electromagnetic spectrum with wavelengths from 1 to 10 mm

or frequency from 30 to 300 GHz – this is also known as the EHF or extremely high frequency band. Current cellular networks use frequencies in the UHF, or ultra-high frequency band (300 MHz to 3 GHz). Although 28 GHz (as used in this paper) is slightly outside the mm wavelength band, this frequency is desirable for cellular networks. This is because at this frequency the air attenuation is relatively low compared to higher frequencies but the bandwidth of available spectra is still relatively high compared to the UHF band [1].

The concept of using mm wavelengths for cellular networks is not new, e.g. [2]. The main benefit of using mm wavelengths is the large amount of spectrum available. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths exceed 500 MHz [1]. This additional bandwidth allows several orders of magnitude greater capacity than current cellular networks. However, the coverage achievable at these high frequencies is significantly less than that from existing base stations [3]. This means many more cellular base stations will be required to offer the same ubiquitous coverage as UHF band networks. Despite coverage limitations the use of mm wavelengths for cellular networks has been trialled by cellular network vendors [4] and proposed for investigation by spectrum regulators [5].

This paper investigates the economic value of spectrum at mm wavelengths. The value of this spectrum is calculated using four models, namely:

- The *benchmarking* comparison - this investigates the value of mm wavelength spectrum based on a global search for recent spectrum valuation results in this band. The benchmarking approach has been studied in lower frequency bands and presented in [6]
- The *discounted cash flow* analysis - this is where the net present value (NPV) of the spectrum band to an operator is calculated by modelling cellular network costs and revenue. This is similar to the methods presented in [7]
- The *real options* approach – this expands from ‘decision making under uncertainty’ in that operators have flexibility in when spectrum is used for cellular networks. The real options approach has been used in papers [8] and [9]
- The *deprivation method* or opportunity cost model – this is used to calculate the value of spectrum using the difference between two business cases, namely where a hypothetical business acquires new mm wavelength spectrum and where the business does not acquire new mm wavelength spectrum [10].

The methods to calculate spectrum value for cellular networks presented in this paper can be used for any spectrum band and in any country. However, to evaluate the accuracy of the model and to calculate the value of mm wavelengths, we have used data from New Zealand. The models are based on both 700 MHz and 28 GHz LTE networks to calculate the value of mm wavelength spectrum

This paper starts by describing the LTE network cost model in section II, and states why accurately costing this network is key to determining the value of spectrum. The four valuation models listed above are presented in sections III to VI. The results and comparative analysis are present in section VII. This includes the valuation of mm wavelengths under different scenarios. The conclusions are presented in section VIII.

II. Cost models

To value spectrum using the models described later in this paper, it is necessary to accurately model the network using this spectrum. This is because the cost component forms the basis for most of the spectrum valuation techniques used. For example, the discounted cash flow model uses the difference in revenue and the cost model to calculate the net present value of spectrum. Similarly, the deprivation cost analysis uses the difference in cost models – the difference in having and not having mm wavelength spectrum. Therefore, the accuracy of the cost model for the network is very important to create accurate valuations for spectrum.

Modern cellular networks use LTE network design similar to that as shown in Figure 1. The cost model used in this paper is a *scorched earth* or greenfields analysis. This means to calculate the network costs as though the network was being built today using modern equipment and technologies. This assumes no existing cellular network infrastructure. To accurately model the scorched earth LTE network, it is necessary to know the capacity requirements (the amount of traffic on the network) and the coverage requirements (the area 'covered' by the cellular network).

The capacity requirements are calculated by analysing the population and mobile device saturation together with the demand forecasts per devices used on the network. This is calculated based on voice, data and messaging traffic types. The coverage requirements are calculated by analysing the geographical area types of each country and the coverage typical from each base station or eNodeB type (e.g. Pico, Micro and Macro cells). The capacity of the network is heavily dependent on the channel bandwidth whereas the coverage achievable is heavily dependent on the frequency used.

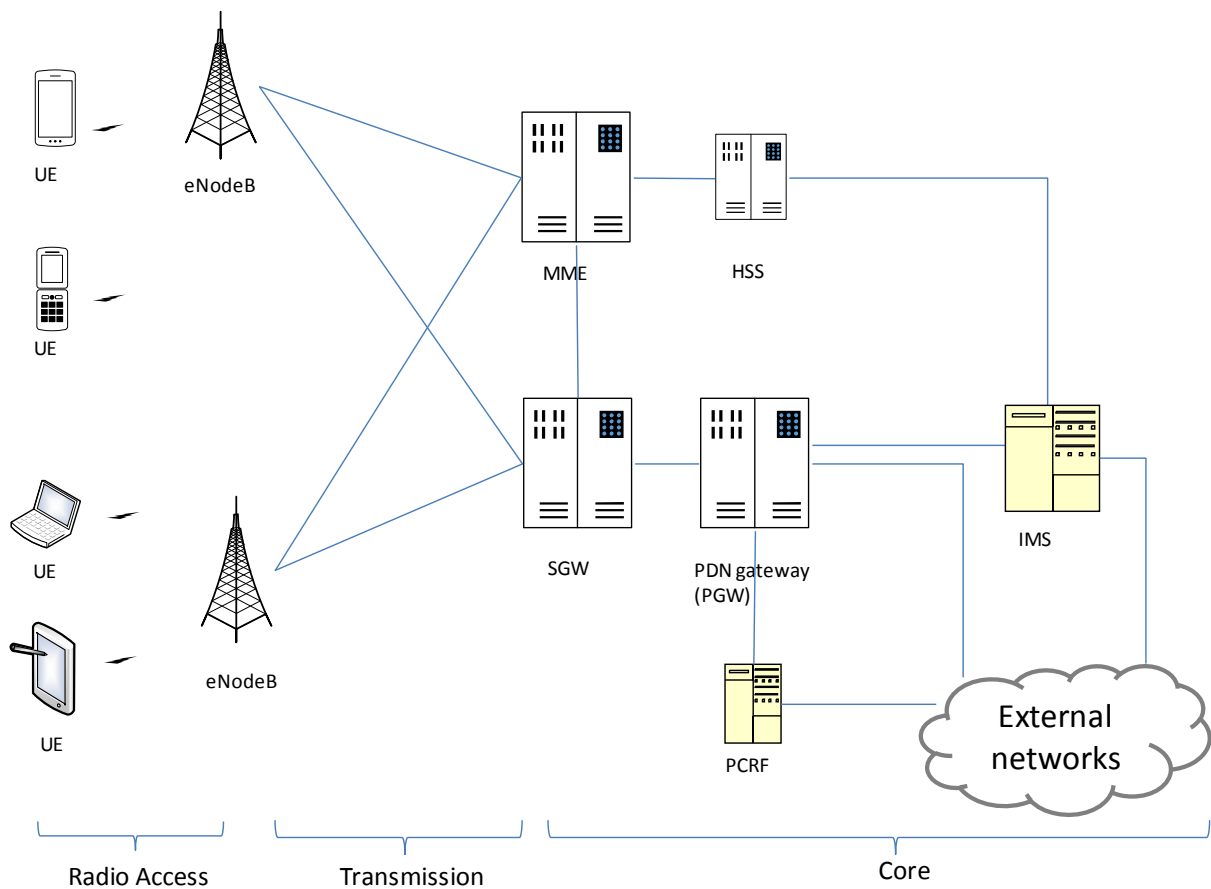


Figure 1. Scorched earth model of the LTE network used for cost analysis

Once the coverage and capacity requirements are known this data can be used to calculate the LTE network equipment required. This is divided into equipment in the radio access network, equipment required for transmission, and equipment required in the core. In the radio access space, the UE (user equipment) can be divided into: low usage devices like (non-smartphones and machine to machine use); medium usage (such as smartphones); and high usage devices (like tablets and laptops). Based on the capacity requirements, the amount of traffic carried in the busy hour over each equipment type in the network is calculated and used to determine how much equipment is needed to meet this traffic demand. Similarly, the frequency and propagation model can be used to calculate the equipment required to meet the coverage demands.

The transmission and core components of the network are also defined by the amount of traffic and devices on the network. The transmission network can be divided into leased ethernet or digital microwave radio. Transmission hubs are used to collate this traffic in geographic areas before using high capacity fibre to backhaul this traffic to the core. Finally, the core can be simplified into the components shown in Figure 1. Here MME (mobility management entity), HSS (home subscriber server), PCRF (policy and charging rules function), SGW and PGW (serving gateway and packet data network gateway), form the basis of the evolved packet core with voice over LTE on the IMS (IP multimedia subsystem).

The overall cost of a cellular network is dominated by the cost of radio access, transmission and core equipment, but there are also significant costs of voicemail, management systems, billing systems, and other indirect costs. The costs of the equipment on LTE networks is very dependent on the vendor used to supply this equipment and is country and operator specific.

III. Benchmarking

The first valuation model presented is the benchmarking approach. This seeks to establish a price for spectrum based on market prices in other countries in similar spectrum bands. The underlying assumption is that the prices will be comparable when market drivers, such as the specific application of the spectrum band, are the same. This information is sourced from spectrum auction results, spectrum trades between companies and from company financial returns.

In practice benchmarking has many challenges. Not all regulators publish data on spectrum allocation publicly. Sometimes only limited spectrum auction information is available with few suitable data points. For example, perhaps the total price paid for spectrum is presented but not the length of the management right for that spectrum. Sometimes there are limiting terms and conditions associated with the spectrum management right which could affect the price paid for the spectrum. Finally, the spectrum data available may only be from countries with very different cellular network markets to that of your target market. There may be a difference in market competition, revenue generated from that spectrum or the spectrum may be assigned to different technology applications.

Benchmarking the value of spectrum at mm wavelengths displays many of these challenges. Initially many countries assigned spectrum in this band not for cellular networks but for fixed licences used in point to point links, for example the use of 26 GHz for digital microwave radio. In the early 1990's spectrum around 28 GHz was assigned for LMDS (local multipoint distribution service) networks. However not many LMDS networks were implemented and competition for LMDS mm wavelength spectrum was limited.

The results of a benchmarking analysis for mm wavelengths is shown in Figure 2. This shows the value of spectrum identified by a price per MHz per population statistic (\$ per MHz Pop). Note that the data

shown in Figure 2 is in NZ dollars. The currency conversion used purchasing power parities (PPPs) - the rates of currency conversion that equalise the purchasing power of different currencies by eliminating the differences in price levels between countries [11]. The population adjustment is at the population in that country in the year of the sale of spectrum.

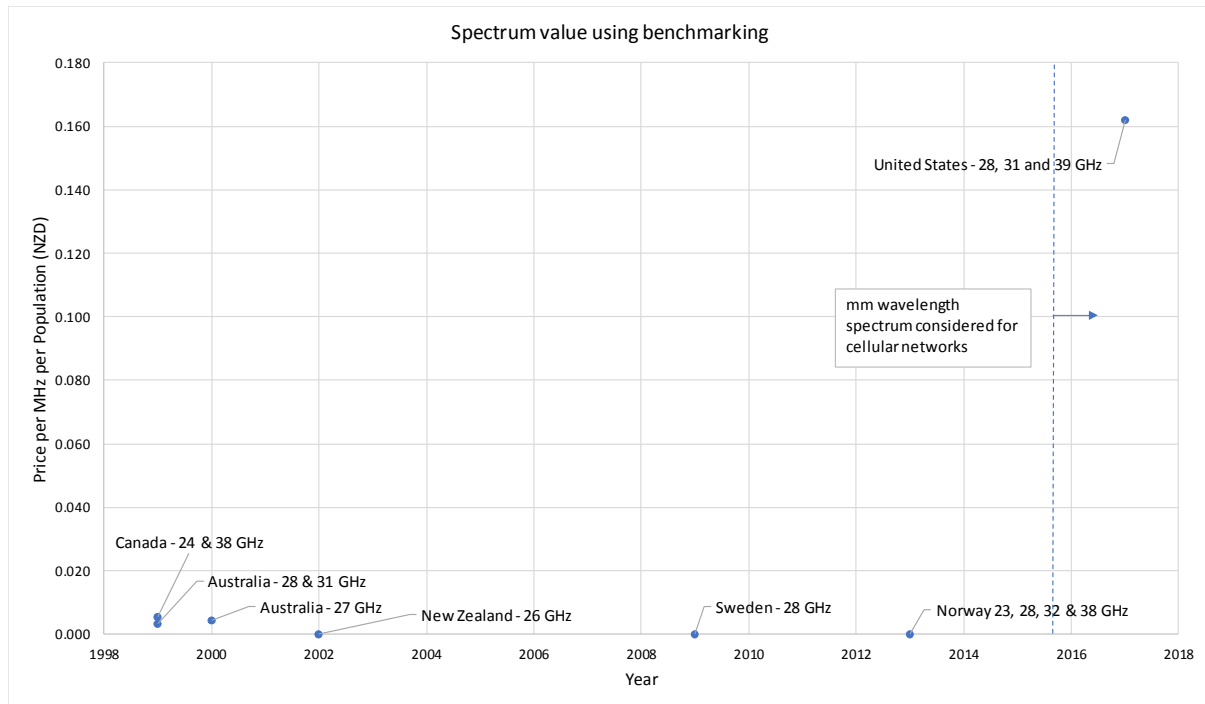


Figure 2. Millimetre wavelength spectrum value using benchmarking. Shown in price per MHz per population in NZD.

This graph shows the relatively low values of this spectrum in the last two decades when demand for this spectrum was low. However recent interest in this frequency band for cellular networks has led to a high benchmarking value for this spectrum in the United States. This was seen in the recent purchase of XO Communications by Verizon [12] showing the increasing \$ per MHz Pop value as shown in Figure 2. This has also been shown in the share price of Straight Path Communications – a company with one of the largest spectrum assets in the US in 28 GHz and 39 GHz. The share price of this company has been reasonably static for over 3 years but by May 2017 had increased from a 52-week low of \$US 15.06 to a high of \$US 164.49.

The recent benchmark result from the United States show how the value of this mm wavelength spectrum is changing. Therefore, the US result should not be removed as an atypical data point. Using this information, we can estimate the value of spectrum in New Zealand using benchmarking as 0.09 \$ per MHz Pop or \$427 M based on NZ population and a spectrum bandwidth of 2 x 500 MHz.

IV. Discounted Cash Flow

The second valuation model presented is the discounted cash flow analysis. This calculates the net present value of spectrum from forecasted future cash flows. The future cash flows are calculated from forecasted revenue less the forecasted costs, and a discounted rate is used to calculate this profit into a single present value. Expressed mathematically this is:

$$NPV = \sum_{t=0}^N \frac{R_t - C_t}{(1 + i)^t} \quad (1)$$

where R is the revenue, C is the cost, discounted by a rate of return i , for time t .

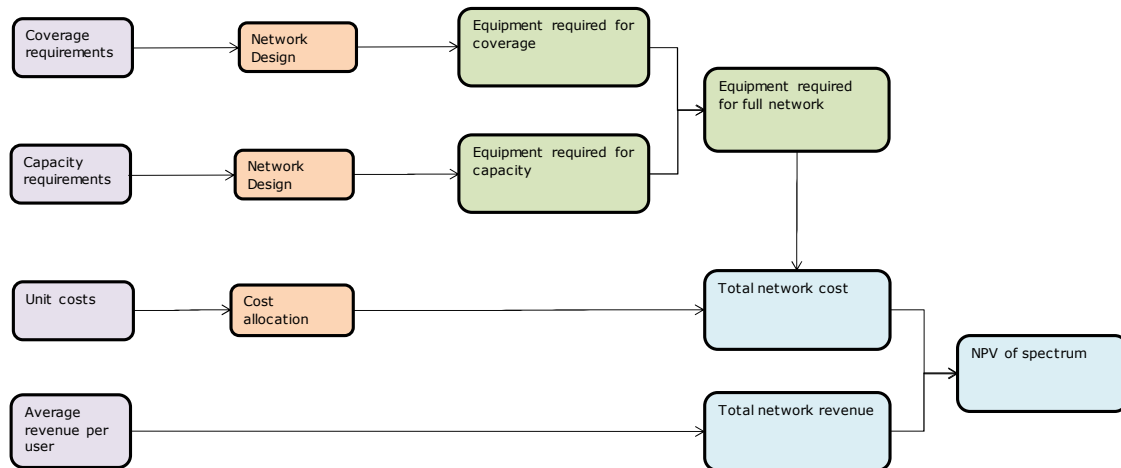


Figure 3. Spectrum valuation model using discounted cash flow

Figure 3 shows the steps used to calculate the NPV of spectrum using discounted cash flow analysis. This paper has already shown the method to calculate the total network cost of using spectrum. Revenue has a huge effect on the value of spectrum when using the discounted cash flow model. This revenue can be calculated based on the revenue generated per MB for data, per voice call and per SMS message. Using this forecast method revenue grows significantly with the forecast growth in traffic over cellular networks. The alternative is to calculate revenue based on an average revenue per user (ARPU) calculation. Using this forecast method, the revenue per user only grows with each user on the network rather than with the exponential growth of wireless traffic.

The results of an NPV analysis of spectrum valuation in New Zealand are shown in Figure 4.

| Model | Frequency | NPV Result | Lot Size | Present value. Price per MHz Pop (NZD) |
|---|------------------|------------|-------------|--|
| NPV model – 700 MHz (ARPU model) | 700 MHz | \$304 M | 2 x 20 MHz | 1.60 |
| NPV model – 28 GHz (ARPU model) | 28 GHz & 700 MHz | -\$251 M | 2 x 500 MHz | -0.05 |
| NPV model – 28 GHz (revenue based on traffic) | 28 GHz & 700 MHz | \$9,929 M | 2 x 500 MHz | 2.09 |

Figure 4. Discounted cash flow analysis of spectrum in New Zealand. Based on a demand and revenue forecasts for 15 years from 2017

The first result of Figure 4 show the NPV of spectrum at 700 MHz. This positive NPV result shows that it is currently economically viable to have a 700 MHz cellular network. The later results in Figure 4 show the NPV of a combined 700 MHz and 28 GHz cellular network. This is using 700 MHz to provide coverage and a mm wavelength network to provide capacity in urban areas. This is a likely rollout scenario for cellular networks using these bands. Calculating the NPV of mm wavelength spectrum using the same revenue as the 700 MHz model creates a negative net present value for this spectrum,

based on current capacity demands. This is to be expected. The capacity forecasts from [13] for New Zealand show a current demand of 2083 MB per Month per device in 2017 and 5217 MB per Month per device in 2021 with a compound interest growth rate of 31%. In the near future, it is not viable to rollout a mm wavelength network because the current UHF band network can meet this demand, and many more mm wavelength sites would be required to provide similar coverage, even in a purely urban setting.

A major assumption here is that the base station costs of mm wavelengths are similar to those using the UHF band. In fact, if the base station costs reduce by 38% and the demand increases beyond that forecasted in the next 5 years then using mm wavelengths becomes more viable in this scenario.

The final result of figure 4 shows the effect of revenue on NPV using the discounted cash flow model. If the revenue is based on the amount of traffic on the network (revenue based on traffic), rather than the amount of people using the network (ARPU), then using mm wavelength also becomes more profitable. However, with the average revenue per user from telecommunications networks remaining static this is a less likely forecast scenario.

The fact that mm wavelength spectrum valuation may increase with increasing network capacity demand, is the subject of the next section of this paper.

V. Real Options

The third valuation model presented is the real options approach. This expands from 'decision making under uncertainty' [8] in that operators have flexibility in how and when spectrum is used for cellular networks. The real options approach is particularly important in calculating the value of mm wavelength spectrum as it considers the option to delay using this spectrum until the capacity demands on the network require large channel bandwidths to meet this demand. As the amount of spectrum available at mm wavelengths is significantly more than that at lower frequency bands, this spectrum becomes more valuable as the capacity demands increase.

A real options analysis starts from the discounted cash flow model and net present value. In fact, the discounted cash flow model is a special case of real options analysis, calculating the net present value where no flexibility is available in the valuation model. Therefore, under real options valuation:

$$\text{Project value} = \text{NPV} + \text{Options value} \quad (2)$$

The options value can be defined by the Black Scholes equation as presented in [14]:

$$\text{Option value} = S \cdot N(d_1) - K \cdot e^{-r_f t} \cdot N(d_2) \quad (3)$$

Here S is current value of the underlying asset, K is the exercise price, t is the lifetime of the option, r_f is the risk-free interest rate, $N(d)$ is a cumulative normal distribution. The first part of equation (3), $S \cdot N(d_1)$, returns the expected benefit of undertaking the investment as soon as possible, based on the present value of future cash flows, while the second term $K \cdot e^{-r_f t} \cdot N(d_2)$, is the exercise price or value of the investment cost, discounted back to present value, weighted by the probability of exercising the option. Here d_1 and d_2 are given in equations 4 and 5, and σ is the project uncertainty:

$$d_1 = \frac{\ln \frac{S}{K} + \left(r_f + \frac{\sigma^2}{2} \right) t}{\sigma \sqrt{t}} \quad (4)$$

$$d_2 = d_1 - \sigma\sqrt{t} \quad (5)$$

| Option | Value | Description |
|----------|----------|--|
| t | 5 years | Regulators typically require networks to be deployed before 5 years |
| S | 1,038 M | Present value of future cash flows using New Zealand mm wavelength cellular network. |
| K | 1,289, M | Present value of investment cost using New Zealand mm wavelength cellular network. |
| σ | 37.6 % | Can be calculated from historic price movements of company, here using 37.6 % |
| r_f | 3.64 % | Risk free rate consistent with bond rates |

Figure 5. Values used in the real options calculation

Using this data and the Black Scholes equations (3) and (4) we calculate $d_1 = 0.379$ and $d_2 = -0.461$ and the cumulative normal distribution, $N(d_1) = 0.648$ and $N(d_2) = 0.322$. This results in an options value of \$326 M.

This results in an overall project value of NPV + Options value = $-\$251 \text{ M} + \$326 \text{ M} = \$75 \text{ M}$.

In this case, the network operator has an option to delay deploying a network using mm wavelengths. From section IV in this paper we saw that taking up this project today has a negative NPV. By exercising the option to defer by 5 years, the operators can utilise the spectrum at a time to make this more profitable, thereby increasing the value of this spectrum.

This result is heavily dependent on the volatility or project uncertainty (σ). As the volatility increases so too does the value of the option. For example, increasing σ to 50% increases the value of the option to \$429.6 M and the value of spectrum to \$178.6 M.

VI. Deprival Method

The final model to calculate spectrum value is the deprival method. This is where the value of spectrum is calculated using two business cases, namely:

1. where the business acquires new mm wavelength spectrum,
2. where the business does not acquire new mm wavelength spectrum.

The difference in the value of the business with and without the spectrum is the theoretical maximum that the business would be prepared to pay for that spectrum. In this case, we compare the value of mm wavelength spectrum using two different LTE cellular network designs, both designed to meet the same forecasted coverage and capacity targets. The first using a heterogeneous network using both UHF and new mm wavelength bands, and the second a purely UHF band network.

Figure 6 shows the steps to calculate the value of spectrum using the deprival methodology. This uses the cost modelling techniques described earlier in this paper.

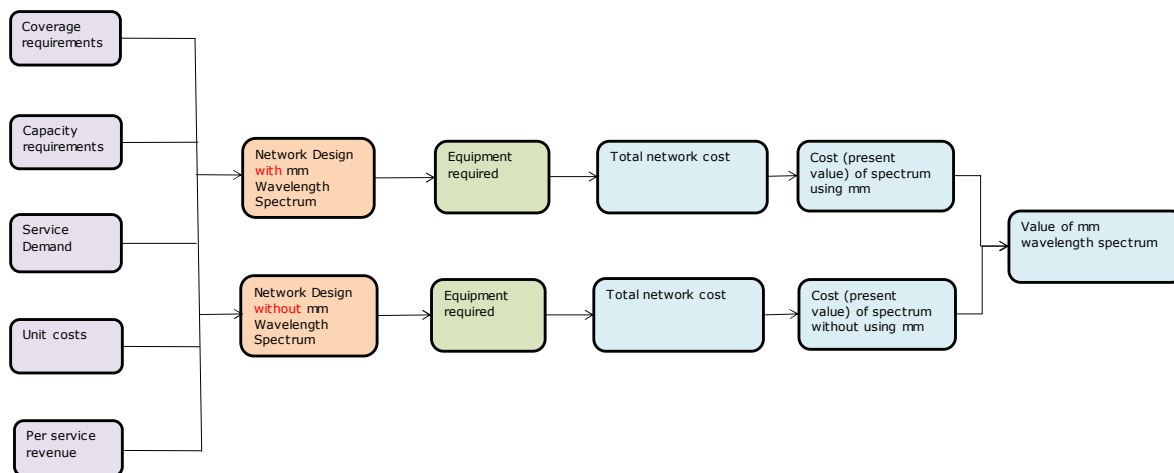


Figure 6. Deprival method to value spectrum

In this case 28 GHz spectrum is used in an urban setting to provide coverage to areas with high capacity demands and 700 MHz spectrum is used to provide coverage to most of the rest of the population.

Figure 7 presents network costs to calculate the value of mm wavelengths using the deprival method. The initial results show a deprival valuation based on Cisco VNI demand [13]. As expected the cost of a mm wavelength network to meet this demand is currently greater than that of a UHF network. Using the deprival value this spectrum is valued by the difference of \$734 M - \$1,289 M = -\$555 M (or -0.11 \$ per MHz Pop).

This result can also be confirmed looking at the difference in NPV values from Figure 4 i.e. the difference in NPV of a combined 700 MHz and 28 GHz network, and a 700 MHz network. Using the results from Figure 4 this is -\$251 M - \$304 M = - \$555 M. This is the same result as above since the revenue is consistent across both business cases and is not needed in this deprival method calculation.

These results show that it is not economically viable to rollout a mm wavelength network to meet the capacity demands of the near future. However, if we now set the forecasted demand to the elevated value of 10 x the current capacity demand, as advertised for 5G [4], then the results are significantly different. In this case, the value of this spectrum is \$2,264 M - \$1,980 M = \$284 M or 0.06 \$ per MHz Pop.

| Model | Demand | Frequency | Lot Size | Cost present value |
|-------------------------------|----------------|------------------|--------------------------|--------------------|
| Cost model – 700 MHz | Cisco VNI | 700 MHz | 2 x 20 MHz | 734 M |
| Cost model – 28 GHz & 700 MHz | Cisco VNI | 28 GHz & 700 MHz | 2 x 500 MHz & 2 x 20 MHz | 1,289 M |
| Cost model – 700 MHz | 10 x Cisco VNI | 700 MHz | 2 x 20 MHz | 2,264 M |
| Cost model – 28 GHz & 700 MHz | 10x Cisco VNI | 28 GHz & 700 MHz | 2 x 500 MHz & 2 x 20 MHz | 1,979 M |

Figure 7. Deprival method to calculate cost

VII. Results

The four valuation techniques investigated in this paper can give quite different spectrum valuation results. This is because these valuation results are based on different methods to calculate spectrum with different inputs to each model. The initial valuation results based on current demand forecasts for New Zealand [13] are presented in Figure 8.

The benchmarking results show a historic low value of mm wavelengths, used primarily for fixed networks, LMDS and satellite communications. The benchmarking value of \$427 M is heavily weighted by recent high values of mm wavelength spectrum purchased in the United States. This shows the recent and increasing value and demand for this spectrum for cellular networks.

The discounted cash flow analysis, based on current capacity demand, shows a negative NPV for this spectrum. The NPV is calculated by the difference in forecasted revenues using this band and network costs to build a mm wavelength network. The negative NPV for mm wavelengths as compared to a positive NPV using the UHF band, shows that the costs are higher using mm wavelengths to meet this demand of capacity within the next 5 years, in New Zealand. This is also confirmed by the fact that management rights for mm wavelength spectrum are already owned by one of the leading cellular operators in this country, and are not being currently used.

| Model | Valuation of mm wavelength spectrum 2017 (NZD) | \$ per MHz Pop - 2017 | Comment |
|----------------------|--|-----------------------|---|
| Benchmarking | \$427 M | 0.09 | This is weighted heavily by recent US results |
| Discounted Cash Flow | -\$251 M | -0.05 | Revenue based on ARPU |
| Real Options | \$75 M | 0.02 | |
| Deprival | -\$555 M | -0.11 | |

Figure 8. mm wavelength valuation results. Based on demand and revenue forecasts for 15 years from 2017.

However, the value of this spectrum increases significantly once demand and revenue forecasts increase. Figure 9 shows the model results by bringing forward the revenue and capacity forecasts by 5 years. This means both the demand and revenue have increased to 5G levels. We now have a positive NPV for this mm wavelength spectrum. This is driven primarily by the increased capacity forecast, requiring more spectrum, and the increase in revenues. This demand cannot be easily met using the limited amount of bandwidth available at 700 MHz.

| Model | Valuation of spectrum 2017 (NZD) | \$ per MHz Pop - 2017 | Comment |
|----------------------|----------------------------------|-----------------------|--|
| Discounted Cash Flow | \$207.1 M | 0.04 | Revenue and capacity forecasts + 5 years |
| Real Options | \$821.8 M | 0.17 | |
| Deprival | \$33.9 M | 0.01 | |

Figure 9. mm wavelength valuation results. Based on bringing forward the forecasted revenue and capacity demands by 5 years.

The real options approach also confirmed the increase in value of spectrum by exercising the option to delay building the mm wavelength network. In this case, the option to delay building the network increased the value from a negative NPV of -\$251 M to a positive NPV of \$75 M.

Finally, the deprival method was used to calculate the value of spectrum by comparing the difference in the cost of networks from a network using, and a network not using, mm wavelengths. As shown in Figure 8, again a negative valuation resulted when using the deprival method, for similar reasons, to meet the capacity demands of the near future. The cost to build a mm wavelength network to meet the forecasted capacity demands within the next 5 years, based on these models, was not economically viable. However, the data shown in Figure 9 shows that when using the deprival method, the value of this spectrum also increases when the capacity demand and forecasted revenue are brought forward 5 years.

Both Figure 8 and Figure 9 show the same relationship between the valuation models, in that the deprival model showed a lower spectrum value than the discounted cash flow which showed a lower value than the real options approach.

There are positives and negatives associated with each of the valuation models presented in this paper. The deprival method does not need revenue forecasts to calculate the value of spectrum. Therefore, there is less estimated or forecasted data used in this analysis. We have seen in the results above that the deprival method is significantly influenced by the capacity forecasts, with very different results depending on these values.

The discounted cash flow analysis uses both revenue and cost to determine the value of spectrum. We have seen in Figure 4 the effect of increasing the revenue and how the revenue forecasts can significantly change the NPV result. However, the discounted cash flow cannot take into consideration the effect of timing on a project, in particular the effect of delaying the rollout of mm wavelengths until required by capacity demands.

The real options approach can take into consideration these project options, and we saw an increase in spectrum value using this valuation technique. However, the real options approach is dependent on σ , the project uncertainty. The project uncertainty is project specific and is difficult to accurately calculate. We saw that increasing σ by 12.4% resulted in an increased spectrum valuation by 138%.

The value of spectrum is likely bounded by the low value of the deprival method and the high value of the real options approach. The results presented by benchmarking are useful to show the historical change in value of spectrum from different markets. It is therefore recommended that these three approaches together be used to estimate the value of spectrum.

VIII. Conclusion

This paper presents four models to value spectrum. We then use these models to value spectrum at mm wavelengths for cellular networks. To value spectrum accurately a thorough understanding of both the economic and engineering use of spectrum is required.

The foundation for the models presented in this paper is an accurate model of the costs associated with the use of spectrum. In our case, we modelled an LTE network using the scorched earth approach using spectrum at both 700 MHz and 28 GHz.

In addition, the economic analysis determines how spectrum is valued. In the discounted cash flow analysis, we calculated the net present value of spectrum using network costs and revenue generated

from that spectrum. The real options approach expanded from the NPV to value the option to delay building a network using mm wavelengths until the demand for capacity justified the network expenditure. In addition the deprival method was used because it excluded the need for revenue forecasts by evaluating the cost of spectrum between two cost models, one with and one without mm wavelength spectrum. Finally, a benchmarking analysis showed the historic value of mm wavelength spectrum based on previously published data.

All four models show that the value of mm wavelength spectrum for cellular networks increases with increasing demand for network capacity. Both the discounted cash flow and the deprival model showed a negative NPV when modelling demand forecasts pre 5G capacity values. However, the value becomes positive when the capacity demands use the high bandwidths of spectrum available at mm wavelengths.

In discussing these results, we showed that there are positives and negatives associated with each of the models. We concluded that the value of spectrum should be given as a range, bounded by the low value from the deprival method and the high value from the real options analysis. Benchmarking is also of interest showing the historical value of spectrum. This paper showed the range of values for mm wavelengths is large i.e. 0.01 to 0.17 NZ \$ per MHz per Pop based on initial 5G capacity forecasts in New Zealand. This is indicative of the change in value of this mm wavelength spectrum as it becomes more popular and in demand for cellular networks.

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