Measured electromagnetic radiation exposure levels around OneNZ mobile base stations – Historical summary

Introduction:

OneNZ formerly known as Vodafone, routinely undergoes a field monitoring program to measure the total electromagnetic radiation field strength around its mobile base stations. The measurements are summarised in yearly reports produced “EMF Services NZ” which can be found on the Te Whatu Ora Health New Zealand web-sight (*Independent Cellsite Monitoring – Te Whatu Ora - Health New Zealand*, n.d.). The full list of references can be found in the bibliography.

The purpose of this document to analyse the available measurements to assess:

1) Power density statistics – quantify key statistics such as the average and range of the electromagnetic radiation emitted by the mobile base stations.
2) Power density distribution – quantify the distribution of the measurements by year.
3) Power density changes over time – track how the overall measurements have changed over time.
4) Power density changes by location – quantify the changes in power density for a location that had repeated measurements taken.
5) Power density by distance – find the relationship between the power density and the distance from a transmitter where geo-spacial data is given.

Method:

The compliance monitoring was performed in accordance with New Zealand Standard 2772.1:1999. For each cell site a measurement was taken where the highest exposure level for that cell site (which was accessible by the public) was identified. The measurement was taken over a six minute interval, and the average power density for that interval was calculated and recorded as the maximum exposure for that site. Because of this averaging the true peak maximum is unknown and expected to be higher than the recorded maximum. Data of the OneNZ compliance measurements were extracted from the available reports between the years 2003 and 2022 and compiled into a spread-sheet. The data was given as a maximum measured power density for each specific site with a date of measurement. The native units of $\mu W/cm^2$ were converted to mW/m^2.

Section 1) Gives an overview of the general statistics for each year for the maximum measured power density at each site.
Section 2) Shows how the distribution of the measurements has changed over time.
Section 3) Analysed the general change for all sights over time. This was done by graphing the raw data over time. The raw data was filtered to exclude outliers and over-layed onto the raw data to show the general trend over time.
Section 4) Examined the changes at a location measured at different points in time. These were plotted by location to indicate the change for each site. The change in power density vs the change in measurement time was also assessed.
Section 5) Focused on case studies, where geo-spacial power density data around specific sights were available.

More specific data analysis detail is given in the relevant sections.

Results:

Section 1) Power density statistics

The statistics for the measured power density for each year is detailed in Table 1. The rows at the bottom show the statistics for specific data ranges, with the final row containing the statistics for the entire data set from 2003~2022.

Year	Average	Standard Deviation	Minimum	Maximum	Number of Points	Number of Outliers <90%	Average Excluding Outliers
2003	8.7	1.4	6.8	10.2	4	0	8.7
2004	16.3	49.7	0.4	360	53	1	9.7
2005	14.5	30.7	0.1	214.9	58	4	8.1
2006	16.6	17.2	0.3	71.7	46	5	11.9
2007	21.5	37.2	0.7	169.8	40	5	9.1
2008	7.2	5.3	0.7	18.2	13	2	5.5
2009	15.6	12.0	1.2	34	5	1	11.1
2010	63.1	124.6	1.4	369	8	1	19.4
2011	9.2	8.7	1.2	35	15	1	7.4
2012	112.8	253.8	1.5	630	6	1	9.4
2013	22.9	22.9	1.4	77	12	1	18.0
2014	23.3	21.7	3.1	72	9	1	17.2
2015	169.3	277.8	7.2	585	4	1	30.8
2016	48.9	39.7	10.35	153	12	1	39.4
2017	45.7	36.0	15.3	135	10	1	35.8
2018	30.2	18.0	4.95	72	10	1	25.6
2019	41.3	33.4	9.9	112.5	10	1	33.4
2020	52.2	87.5	7.65	297	10	1	25.0
2021	26.5	16.4	9.45	63	10	1	22.4
2022	47.9	37.4	5.4	117	10	1	40.3
2003 ~ 2008	16.2	34.4	0.1	360	214	11	10.1
2009 ~ 2014	33.9	95.3	1.2	630	56	2	16.7
2015 ~ 2022	48.7	75.3	4.95	585	76	3	36.5
2003 ~ 2022	**26.2**	**60.0**	**0.1**	**630**	**345**	**12**	**17.4**

Table 1: Power density statistics

The entire data set from 2003 to 2022 ranges between a minimum of 0.1 mW/m^2 and a maximum of 630 mW/m^2 with an average of 26 mW/m^2 and a standard deviation of 60 mW/m^2.

The high standard deviation of each data set indicates that the spread of the data varies significantly. Comparing the maximum column to the average, it is clear the data contains high value outliers. The number of outliers is quantified by counting how many data points are above the mean by 1.28 standard deviations indicating that data point is above the 90th percentile of the data range. The final column shows the average excluding these outliers.

The average excluding the outliers between the years 2003 and 2008 ranges from 5 mW/m^2 to 12 mW/m^2 with an overall average of 10 mW/m^2, while in the years 2015 to 2022 the average is greater ranging from 22 mW/m^2 to 40 mW/m^2 with an overall average of 37 mW/m^2. Similarly in the years 2004 to 2013, the minimum value measured ranges from 0.1 mW/m^2 to 1.5 mW/m^2, while the minimum between the years 2015 and 2022 is higher, ranging from 5 mW/m^2 to 15 mW/m^2.

Section 2) Power density distribution

The distribution of the measurements can be assessed by calculating the percentage of data points above or below a power density threshold as seen in Table 2. The threshold is indicated in the first row. The table cells are colour-coded with red representing 100% and green representing 0%.

As an example, the interpretation for the year 2006 is: 76% of measurements were above 5 mW/m^2; 52% were above 10 mW/m^2; 35% were above 15 mW/m^2; and 0% were above 75 mW/m^2. The percentage of data below a threshold can be calculated by subtracting the percentage 'above' from 100 (if 76% are above 5 mW/m^2, then 24% are below 5 mW/m^2).

Year	Units	Measurements Above Threshold											
	mW/m^2	5	10	15	20	25	30	35	40	45	50	75	100
2003	%	100	25	0	0	0	0	0	0	0	0	0	0
2004	%	60	21	19	15	8	8	6	6	4	4	2	2
2005	%	60	29	26	17	10	10	9	9	7	7	3	2
2006	%	76	52	35	30	22	17	17	11	9	4	0	0
2007	%	53	35	25	23	20	18	18	18	18	18	13	5
2008	%	54	15	15	0	0	0	0	0	0	0	0	0
2009	%	80	80	40	20	20	20	0	0	0	0	0	0
2010	%	63	63	63	50	50	50	38	13	13	13	13	13
2011	%	73	27	13	7	7	7	0	0	0	0	0	0
2012	%	33	33	33	33	33	33	33	17	17	17	17	17
2013	%	67	58	50	50	42	25	25	17	17	8	8	0
2014	%	78	67	56	56	44	22	11	11	11	11	0	0
2015	%	100	75	75	75	75	75	50	50	50	50	25	25
2016	%	100	75	75	75	75	75	50	50	50	50	25	25
2017	%	100	100	92	83	67	67	58	42	33	33	17	8
2018	%	100	100	100	70	70	60	60	50	30	20	10	10
2019	%	90	90	90	70	60	50	30	10	10	10	0	0
2020	%	100	90	90	50	50	50	40	40	40	30	20	10
2021	%	100	80	60	50	50	50	30	20	20	20	10	10
2022	%	100	90	80	80	60	60	50	40	40	40	30	10

Table 2: Percentage of measurements above a power density threshold

The data can be broken up into ranges that have similar characteristics shown in Table 3.

2003~2008 the majority (67%) are below 10 mW/m^2, and 25% are above 15 mW/m^2.
2009~2014 the majority (55%) are below 15 mW/m^2, and 23% are above 30 mW/m^2.
2015~2022 the majority (54%) are above 30 mW/m^2, and 25% are above 50 mW/m^2.

Year	Units	Measurements Above Threshold											
	mW/m^2	5	10	15	20	25	30	35	40	45	50	75	100
2003 ~ 2008	%	63	32	25	19	13	12	11	9	8	7	4	2
2009 ~ 2014	%	68	52	41	34	30	23	16	9	9	7	5	4
2015 ~ 2022	%	99	91	83	67	58	54	42	33	28	25	13	8

Year	Units	Measurements Below Threshold											
	mW/m^2	5	10	15	20	25	30	35	40	45	50	75	100
2003 ~ 2008	%	36	67	75	80	86	88	89	91	92	93	96	98
2009 ~ 2014	%	30	48	55	64	70	75	82	91	91	93	95	96
2015 ~ 2022	%	1	9	17	33	42	46	58	67	71	75	87	92

Table 3: Percentage of measurements above and below a threshold for a data range

Section 3) Power density changes over time

The data set contains some high value outliers. This was addressed by filtering the data to exclude outliers. The filtering was done in four stages, two stages to exclude the outliers, and two stages of moving average filters.

The first stage of filtering compared each raw data point to a threshold which was set as the mean plus two standard deviations for its data range. The data ranges used were: 2003~2008, 2009~2014 and 2015~2022 as identified in the previous section. If the data point was greater than this threshold, then the filtered data point was taken as the average of its neighbouring two values plus the original data point scaled by a factor of 0.25. If the data point was below the threshold, then the raw data value was retained. This type of filtering only affects the top 2.3% of the data points.

The second filter stage is identical to the first, but using the filtered data as an input with the new filtered mean and standard deviations used for setting the threshold. Figure 1 shows the output with the 'Filtered' data in blue with the raw data represented by green crosses. Note power density is represented on a logarithmic scale.

The third and fourth filter stage used a moving average window applied to the processed data. The data from 2003 to 2007 had approximately 40 data points per year, then subsequent years had 10 data points per year. The data range from 2003~2007 used a 41 point moving average, while the data from 2008~2022 used an 11 point moving average. The result is displayed as the red 'Moving Average' line in Figure 1.

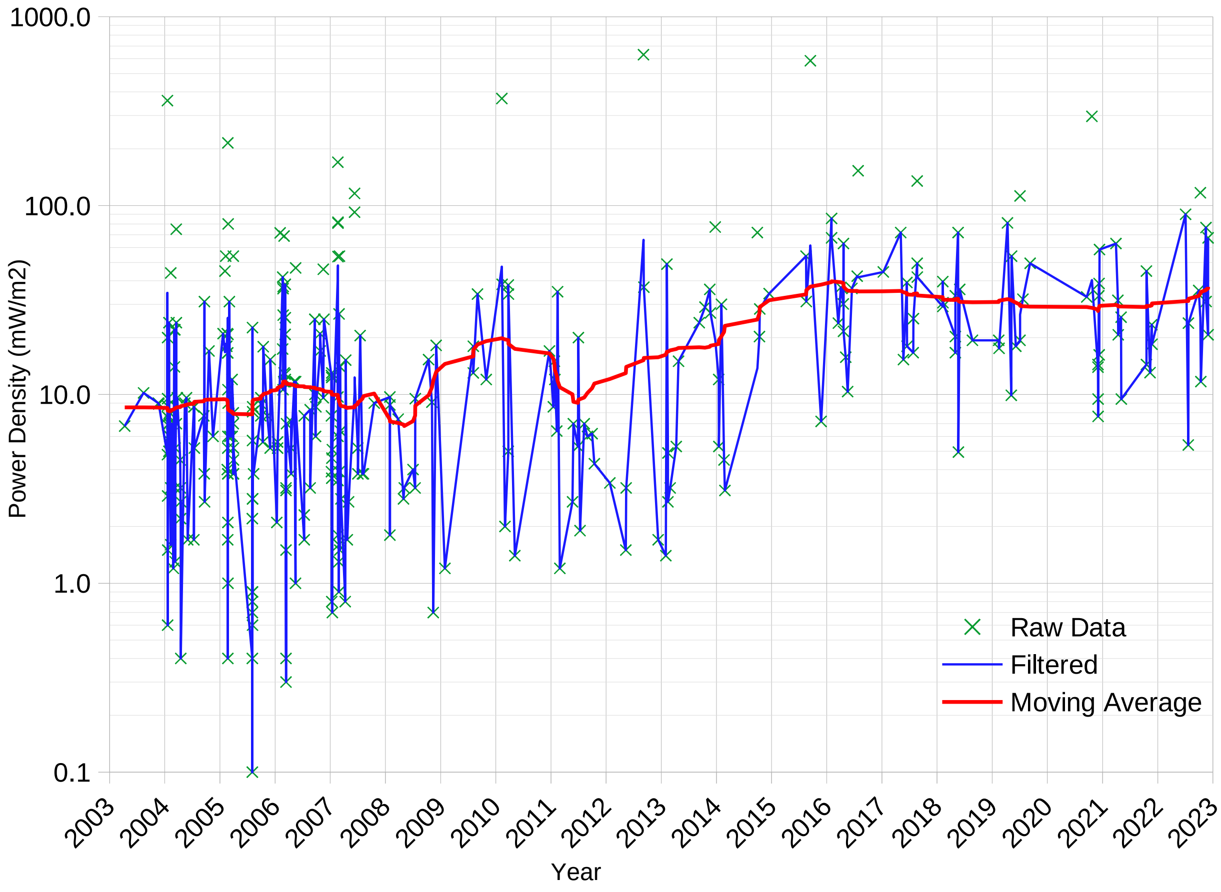

Figure 1: Historical trends with raw data

Figure 2 shows the ‘Moving Average’ on its own with a linear scale for the power density so the trend is more clearly visible.

From the years 2003 to 2008 the average measurements around the 10 mW/m^2 range.

From 2009 to 2015 there is a gradual increase in the average measurements to a value of 40 mW/m^2 with the trend most noticeable between 2012 and 2015.

From 2016 to 2021 the average reduces to 30 mW/m^2, but starts to increase rapidly in 2022.

Overall there is at least a 3 fold increase in the average power density when comparing data from 2003~2008 with the data from 2015~2022.

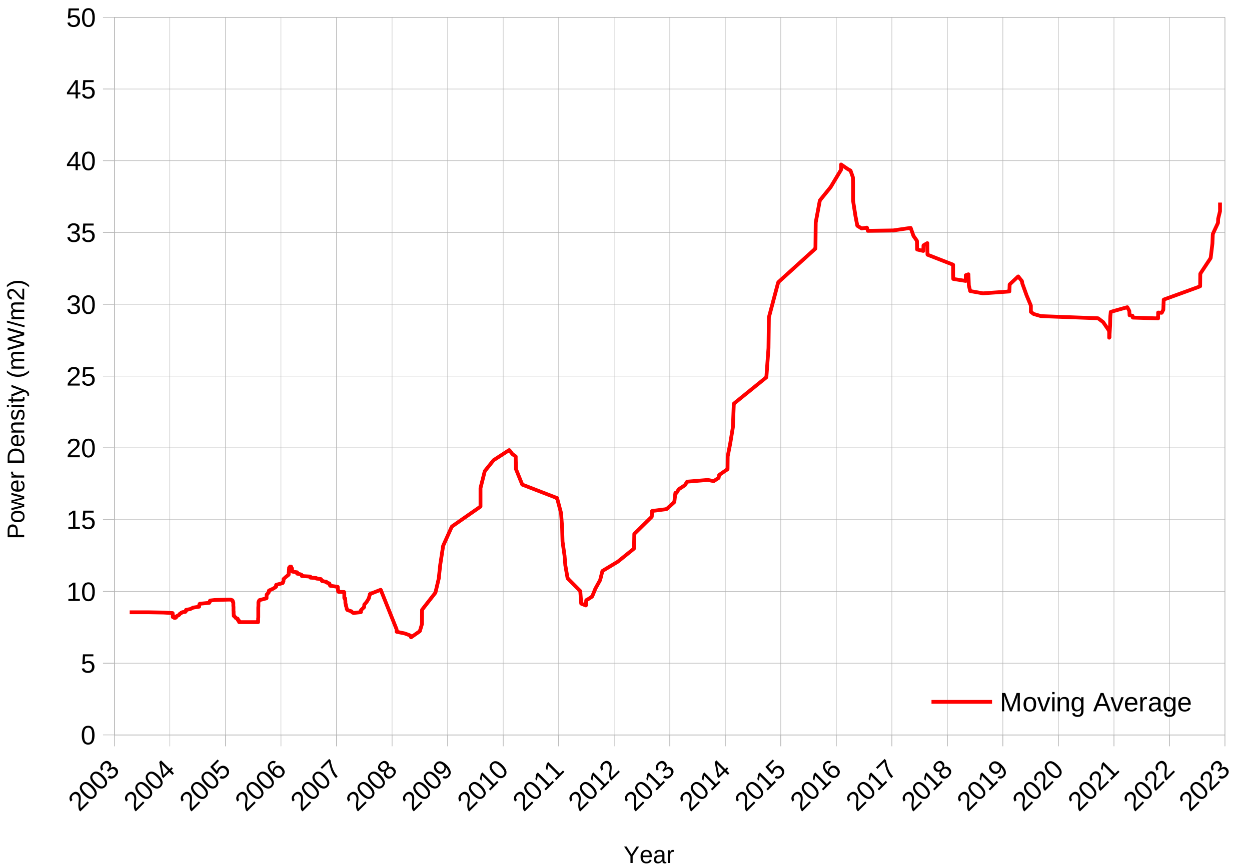

Figure 2: Historical trends moving average on linear scale

Section 4) Power density changes by location

The full data set contains some duplicate locations, measured at different times. The changes to these locations are graphed in Figure 3.

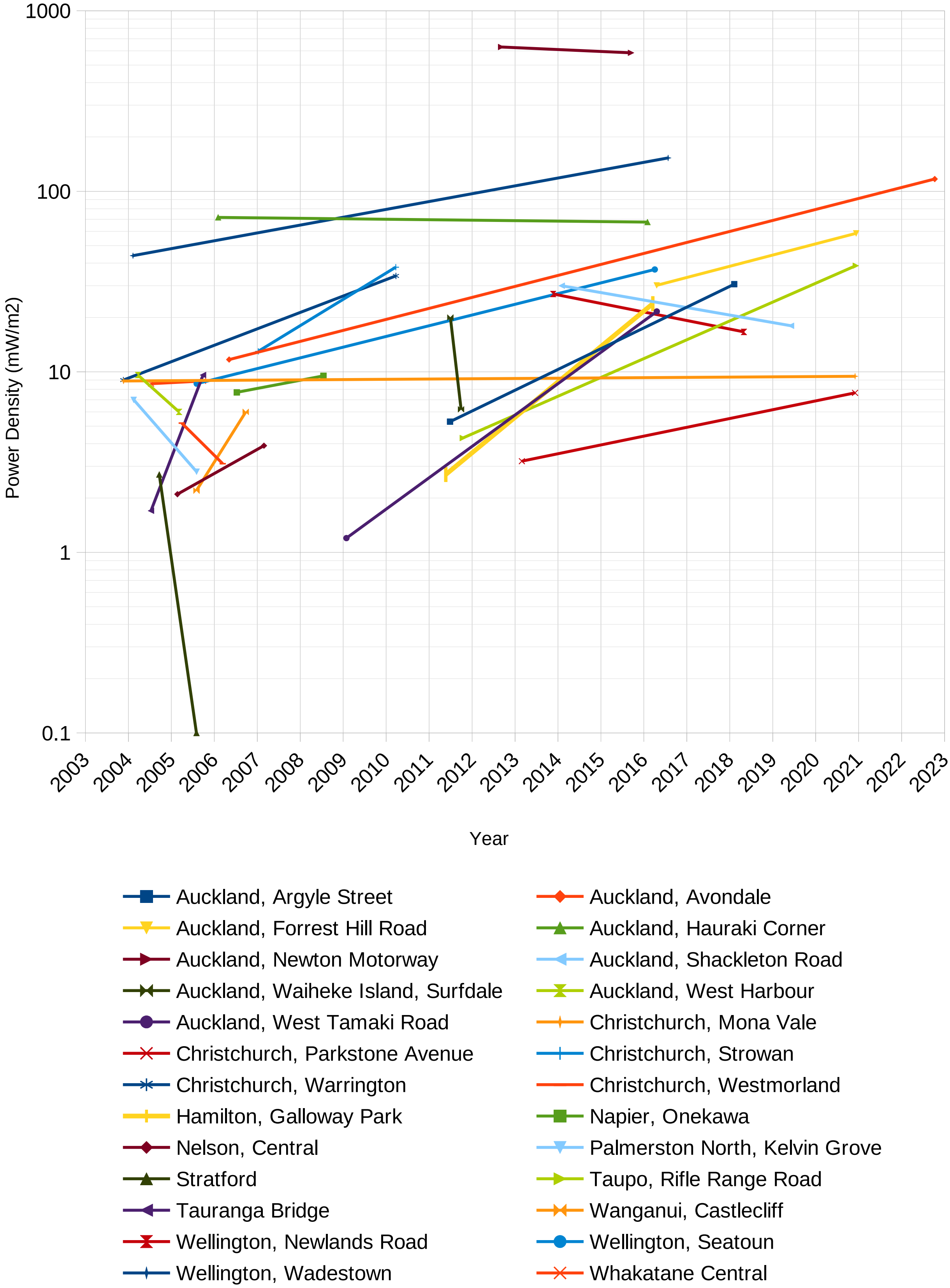

Figure 3: Duplicate locations raw data

There are a total of 25 duplicate locations excluding the outlier at “Auckland, Newton Motorway”. Of these locations: 7 show a decrease in power density (negative slope); 3 show no significant change in power density (very small slope); and 15 show an increase (positive slope). The slop change was determined by calculating if the change of power density is greater than 10% of the average power density between two points.

The cell sites that show a reduction had an average starting power density of 15 mW/m^2, with an average decrease in power density of 7 mW/m^2. The cell sites that have an increase had an average starting power density of 10 mW/m^2 and increased by 30 mW/m^2 on average.

The changes in power density is better visualised by plotting the change in power density by the change in time, graphed in Figure 4.

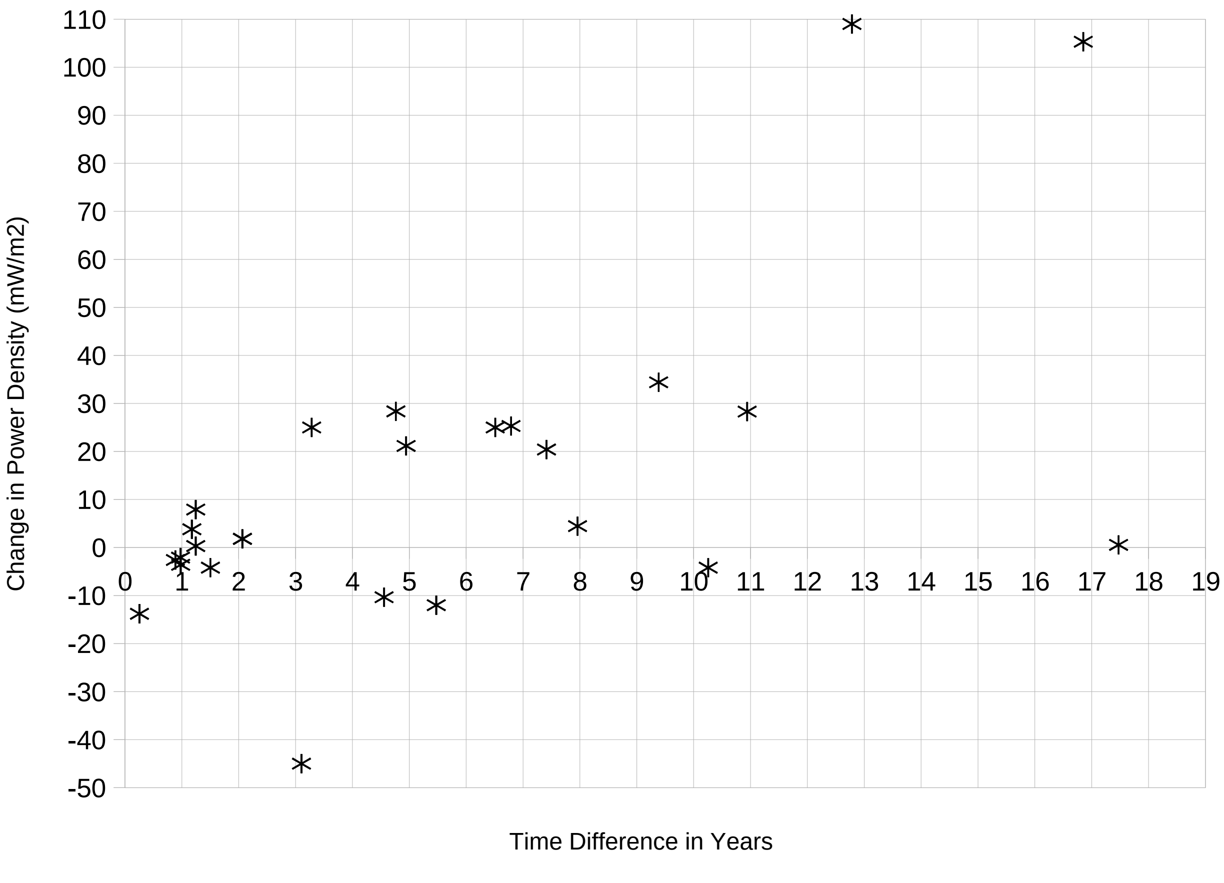

Figure 4: Change in power density over change in time by location

The majority of the data points are above the x-axis indicating an increase in power density. Points that lie very close to the x-axis suggest a small change while points that are significantly below the x-axis indicate a decrease in power density. Note, the original starting power density is not shown here, only the change in power density can be seen.

The overall average increase in power density is 16 mW/m^2 for all the duplicate locations excluding the outlier. The increase in power density is in agreement with the general increase observed with the full data set.

Section 5) Power density by distance

The Vodafone cell-site monitoring summary report for the period of June 2013 to May 2014 (Dirksen, 2014) contained more detailed data of the power density measured at different locations for ten transmitter base stations. The data shows an aerial map of each cell location, with the magnitude of the power density labelled at the specific measurement location. The distance between the transmitter and the measurement location was estimated using google maps 'measure distance' tool for each location.

The power density at a given distance away from a transmitter should follow the inverse square law below:

$$S = g \frac{P_t}{(4\pi d^2)}$$

Where 'g' is the antenna gain constant, which is a measure of the ability of the antenna to direct the power in a given direction. 'P_t' is the power of the transmitter, 'd' is the distance from the transmitter, and 'S' is the calculated power density.

Out of the 10 measurement sites, only five displayed this type of correlation. Three of the sites that had the most consistent correlation in terms of gradient are shown in Figure 5.

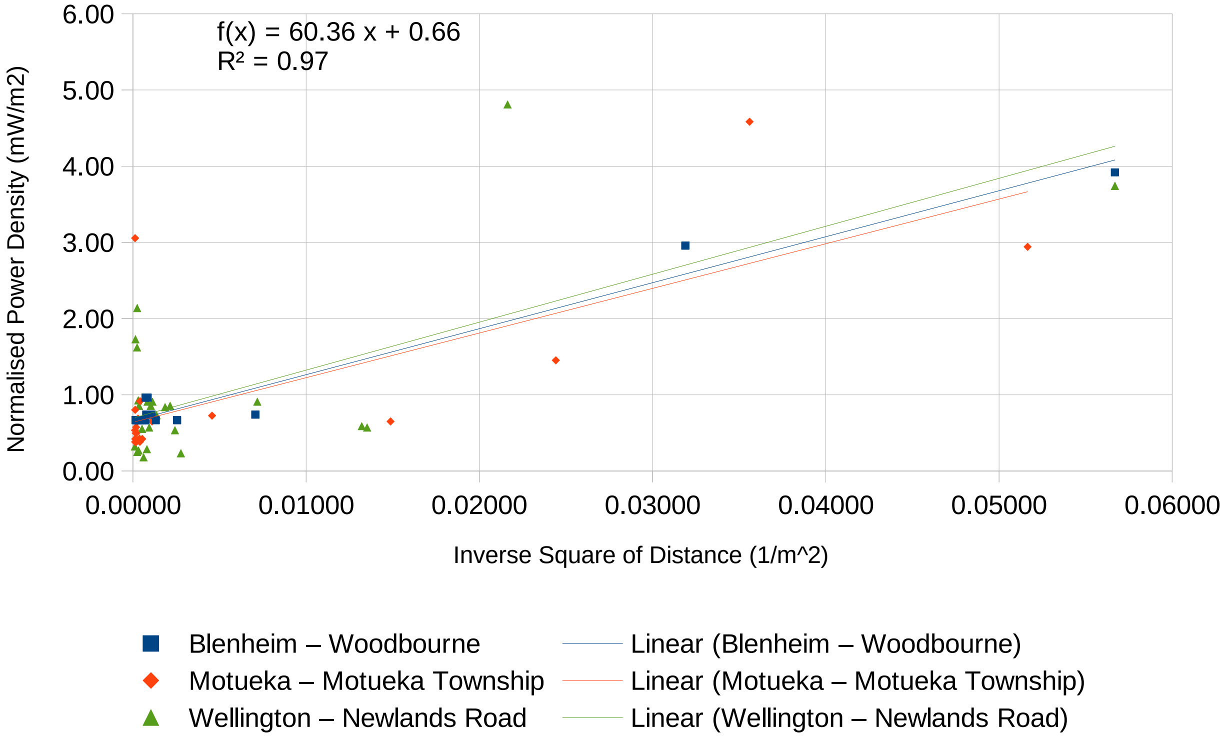

Figure 5: Inverse square distance approximation

The Y axis contains the 'normalised' power density, by dividing each measurement at a cell site by the average of all measurements for that site. The X axis contains the inverse square of the distance or $1/d^2$ (0.04 = 5 m; 0.01 = 10 m; 0.0025 = 20 m ect.). The approximation becomes more valid for larger distances with the majority of points locating very close to the trend lines. There is however quite a large degree of scatter within this data set.

In theory, the power density is inversely proportional to the square of the distance from the transmitter. However in practice, the power density is affected by other factors such as line of sight, obstructions, reflections form nearby structures, transmitter orientation and direction, and the antenna radiation pattern. As the latter factors could not be practically assessed, a clean relationship between distance of the measuring site and power density could not be found.

The graph in Figure 6 shows the a scatter plot of measured power density as a function of distance for all ten sites.

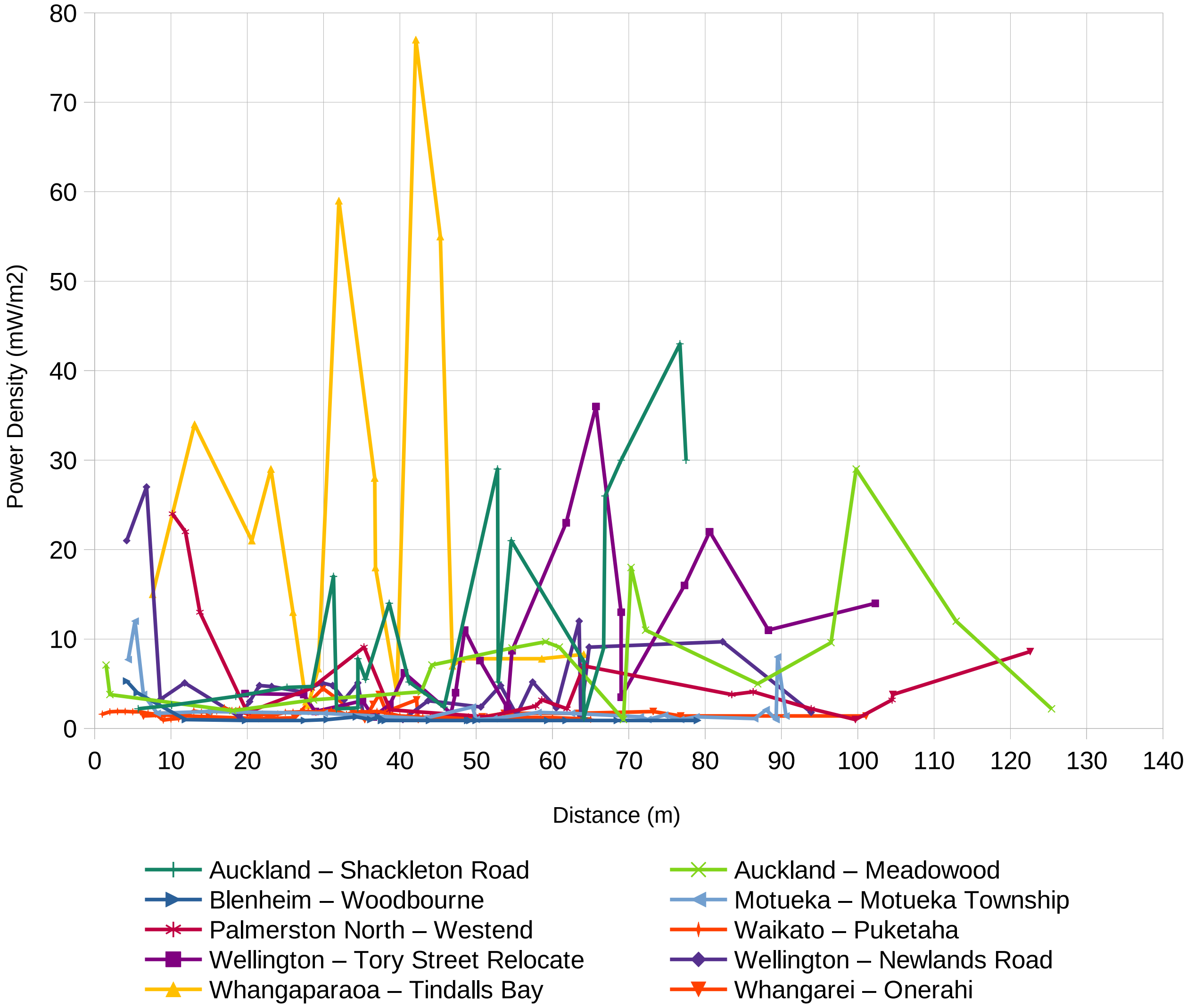

Figure 6: Power density as a function of distance

There is substantial scatter in the dataset, with some transmitters having significantly more power such as Whangaparaoa, compared with other sites such as Whangarei. There is usually a local peak close to the transmitter (<20 m) e.g. Palmerston North – Westend. In many cases the maximum measurement was taken at some distance from the transmitter between 30 m and 110 m as seen with Auckland, Whangaparaoa, Wellington. Generally the power density did decrease with sufficient distance.

One transmitter located on Puketaha Road in the Waikato had data measured directly in line with the south-east sector and is displayed in Figure 7. This cell site did not have any major obstructions such as nearby buildings, and was measured on straight road eliminating the orientation variable. The increase in power density between 15m and 40m could be caused by the antenna radiation pattern. Typical cell tower antennas are designed to be directional, with the main beam angled slightly downwards so the highest measurements are expected in the main beam (Baltrėnas et al., 2012). Measurements that are outside of the main beam gradually reduce with distance.

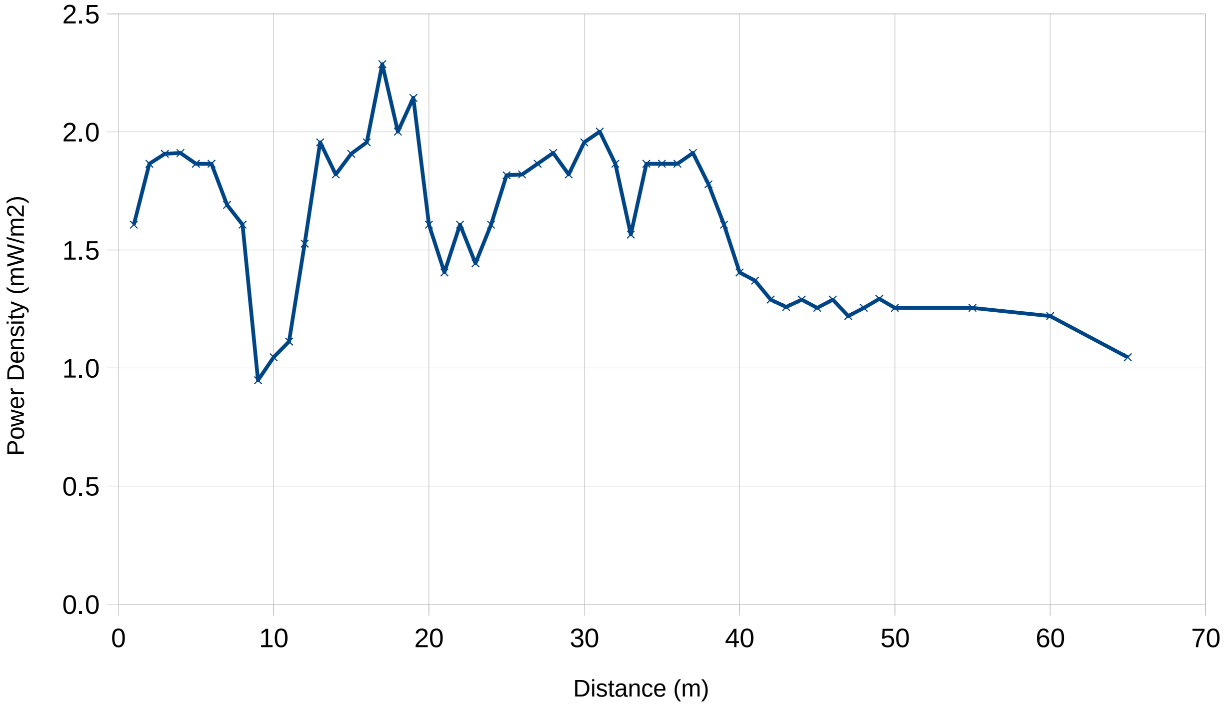

Figure 7: Waikato – Puketaha Road raw data

Conclusions:

The spread of measurements varies substantially between mobile base stations with a range between 0.1 mW/m^2 to 630 mW/m^2.

The typical average excluding the outliers between the years 2003 and 2008 is 10 mW/m^2, while in the years 2015 to 2022 the typical average is 37 mW/m^2.

The distribution of the data changes significantly with time. From the years 2003 to 2008 the majority of measurements (67%) are below 10 mW/m^2, and 25% are above 15 mW/m^2. While from the years 2015 to 2022 the majority of measurements (54%) are above 30 mW/m^2, and 25% are above 50 mW/m^2.

The overall measured power density has increased by a factor of at least three from the years 2003 to 2022.

The 26 locations where measurements were repeated shows an overall increase of 16 mW/m^2. 7 locations had an average decrease of 7 mW/m^2 from an average starting level of 15 mW/m^2. 15 locations had an average increase of 30 mW/m^2 from a starting level of 10 mW/m^2.

Some of the data from the 2013~2014 dataset did suggest an inverse square distance relationship with power density measurements, however this was only applicable to some parts of the dataset.

Overall there is an increase in power density as the years progress.

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