An Analysis of the Usage of the 2.4 GHz and 5 GHz Radio Bands in Antwerp

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Contents

1 Introduction

Most of the radio spectrum requires a license to operate on. Devices emitting Radio Frequency (RF) energy without a license often use one of the unlicensed Industrial, Scientific and Medical (ISM) radio bands. The most well-known of these bands is the 100MHz wide band centered around 2.45 GHz, often called the 2.4 GHz band. Many consumer devices such as wireless mice and keyboards, bluetooth headphones and Radio Controlled (RC) cars communicate in the 2.4 GHz band. Furthermore most IEEE 802.11 (Wi-Fi) routers operate in the 2.4 GHz band. In addition 802.11ac routers operating in the 5 GHz range often use the 5 GHz ISM band (which actually ranges from 5.725 GHz to 5.875 GHz). Some other bands in the 5 GHz are also allowed for 802.11ac, although more restrictions, such as indoors-use only, apply there [1]. These ISM bands were originally intended and still used for devices emitting RF energy for purposes other than communication. The most common such application is the microwave oven. All this leads to high interference in these bands. In this paper, we investigate how bad this 2.4 GHz and 5 GHz interference actually is in the city of Antwerp.

To measure this interference we use the City of Things (CoT) network, operated by research institute imec[1]. This network consists of hundreds of sensors and wireless gateways positioned around the city of Antwerp. On 11 of these gateways, we sampled activity on the 2.4 GHz and 5 GHz bands every 2 minutes for 12 days, including a Monday-to-Sunday week. The main motivation of this experiment is to investigate whether interference around the gateways is significant enough to pose a problem for the network. Next to the general magnitude of the interference, we look for patterns in daily and weekly variation of the interference.

2 Measuring Interference

All used nodes have a COMPEX WLE900VX-7A network adapter, containing a Qualcomm Atheros QCA9880 wireless chipset. This 802.11ac chipset, along with all other 802.11ac and 802.11n chips by Qualcomm Atheros support a mode called *spectral scan*. In this mode the chip can scan the activity on all frequencies it supports. This activity is not limited to 802.11 traffic, but is influenced by any received signal. In this mode, the chip acts as a simple spectrum analyzer. The Free and Open-Source Software (FOSS) ath9k and ath10k drivers, respectively for the 802.11n and 802.11ac Qualcomm Atheros chipsets, support this mode. Each scan is performed over a period of 4 µs. Every scanned channel is divided into 64, 128 or 256 equally wide bins. For the full channel the noise floor and Received Signal Strength

[1] `https://www.imec-int.com/en/home`

Indicator (RSSI) are reported, along with a magnitude for each bin. This magnitude incidates how the power within the channel was divided across the bins. We provide an overview of how to interpret these values in section 2.2.

2.1 Settings

The ath10k version of spectral scan offers fewer options than the ath9k version. For instance the option to increase the scan time from 4 µs to 2044 µs is absent in ath10k. The only missing option relevant to our case is the *chanscan* mode of spectral scan. When this mode is triggered, the driver gathers a configurable number of samples for every channel it supports. We emulate this behaviour using the *background* mode, which continuously scans the chipset's currently configured channel as long as it is not sending or receiving. We combine this with an *iw scan* command, which listens for access point beacons for a provided list of frequencies. When providing *iw scan* with a list of all supported frequencies, this closely emulates the *chanscan* behaviour.

2.2 Interpreting spectral scans

Before going into the interpretation of this specific data, we provide a quick overview of the dBm unit, often used to express power ratios. The regular decibel (dB) unit is a dimensionless unit. The dBm unit instead expresses absolute power in reference to watt. 0dBm is defined as 1 milliwatt (mW). For each increase of 3dBm, the power in mW doubles, and for each increase of 10dBm, the power is multiplied by 10. Milliwatt-to-dBm conversion is calculated using the formula

$dBm = 10log_{10}(\frac{x}{1\,\mathrm{mW}})$, with x the power in mW.

A negative dBm power simply means the power is less than 1 mW. By using dBm, very small or large power values are often avoided. As power attenuates quadratically with distance, useful power values can vary dramatically.

For each channel scan, the driver reports the noise floor and RSSI value. The noise floor value is a hard-coded estimation for every channel and ranges between -94dBm and -108dBm. This value is the expected power of all noise in a channel combined. This includes noise sources such as thermal noise and cosmic noise. The chipset can only receive a signal whose power exceeds this noise floor. The RSSI value is a (unitless) integer indicating, as the name implies, the received power in the channel. While the existence of this value is part of the 802.11 specification, its calculation is not. As a result every manufacturer calculates the RSSI differently. Atheros chips follow a rather simple formula: subtracting the noise floor from the current signal strength in dBm results in the RSSI. As a result, the noise floor and RSSI are enough to estimate the signal strength in a channel: a noise floor of -96dBm and an RSSI of 40 indicate a received signal of -56dBm [2]. The RSSI reported by Atheros is often limited to 60. As RSSI was originally intended to estimate signal quality within the driver, values above 60 were not interesting; -36dBm (assuming a noise floor of -96dBm) already indicates excellent reception. It appears however that in this spectral scan mode, the hardware does return RSSI values of over 60.

The per-bin magnitudes indicate how power is divided within the channel. To understand these values, some background about radio signaling is needed. Signals in radio communication are usually created using a technique called *IQ modulation*. With this technique, the final signal is a combination of two separate signals (the in-phase or I and the quadrature or Q signals) whose phases are exactly 90 degrees apart. By changing only the amplitude of the I and Q signals, the resulting signal's amplitude and phase can attain any value. The reported bin magnitude $b(i)$ for bin i is the sum of the absolute values of the I and Q signals' magnitudes. This magnitude in turn is the amplitude squared. The per-bin power scales quadratically with this magnitude value: if bin i has twice the magnitude of bin j, bin i's share of the channel's power is four times as large as bin j's. We can compute a coefficient $c(i)$ for every bin $i \in [1, n]$ as follows:

$$c(i) = \frac{b(i)^2}{\sum\limits_{j=1}^{n} b(j)^2} \text{ (Note that every } c(i) \in [0,1] \text{ and } \sum\limits_{c=1}^{n} c(i) = 1.\text{)}$$

As the dBm power values computed from the noise floor and RSSI are not linear but rather logarithmic, we cannot simply multiply by $c(i)$ to get each bin's power value. Instead we first convert $c(i)$ to a logarithmic value:

$$c_{log}(i) = 10log_{10}(c(i)).$$

As $log(a * b) = log(a) + log(b)$, we add this coefficient to the total logarithmic power to calculate each share's power:

$$nf + RSSI + c_{log}(i).$$

Noting that $log(a/b) = log(a) - log(b)$, writing the formula using only the parameters returned by the spectral scan results in

$$nf + RSSI + 10log_{10}(b(i)^2) - 10log_{10}(\sum_{j=1}^{n} b(j)^2)$$

The earliest reference to this formula being used with the FOSS Atheros drivers was in an email on the ath9k-devel mailing list by Zefir Kurtisi [3], in reply to the Request For Comments (RFC) on spectral scan support by Simon Wünderlich. As far as we know neither this formula nor the calculation of its parameters were ever confirmed to be correct by Qualcomm Atheros. This remains an educated guess by the community.

For the remainder of this document, we will only take the noise floor and RSSI values into account. We saw no need for a granularity of the measurements lower than 20MHz.

3 Measurements

At first we measured the spectrum on every channel in both the 2.4 GHz and the 5 GHz band every 10 minutes. The visualizations of the gathered data using Simon Wünderlich's FFT_eval tool[2] showed that a shorter time between scans would be useful. There were often large variations between two subsequent samples. Additionally we noticed some extreme outliers. Occasionally a received signal strength of 129dBm or 8GW was reported. As a steady 8GW supply would require over 35 million solar panels [4], this is clearly an erroneous measurement. Although this was a fairly rare phenomenon, it still occurred up to a few times in each node's almost 10 million daily samples. To avoid such erroneous samples, we remove the n highest signal strength measurements from every scan. The choice of n depends on the sample size. For a single-channel 2.4 GHz scan, consisting of around 210 samples, we remove the top 5. We then consider the maximum signal strength among the remaining samples as the measured strength within the channel.

We perform one scan per minute, alternating between 2.4 GHz and 5 GHz. As each scan takes at least 25 seconds to complete, we chose not to lower this interval any further. This generates around 860MB of raw data per node per day. Even when only considering the maximum signal strength per sample, we still need some way to condense this to a more digestible format. We experimented with some smoothing algorithms and had the best results with the Savitzky-Golay filter[3]. A detailed analysis of the filter was considered outside of the scope of this document, but we note that it is a digital filter intended for equally spaced data points that smooths data through convolution. We always used polynomials of degree 3. The only other parameter is the window size. The higher the window size, the smoother the final result. Figure 1 shows the resulting smoothings for 2

[2] https://github.com/simonwunderlich/FFT_eval

[3] `https://en.wikipedia.org/wiki/Savitzky%E2%80%93Golay_filter`

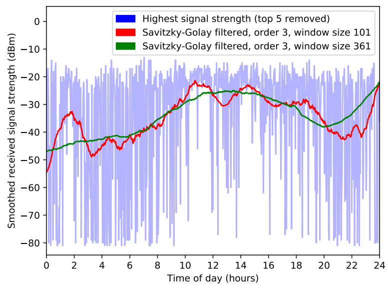

Fig. 1: Savitzky-Golay smoothing.

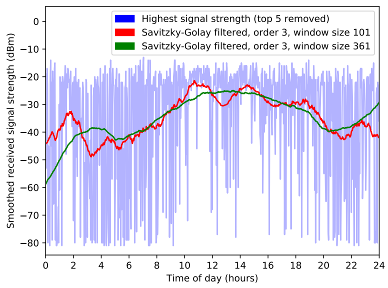

Fig. 2: Savitzky-Golay smoothing, 1 additional hour of data point for each end.

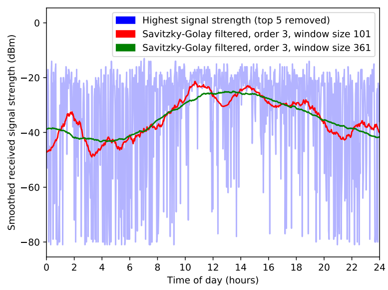

Fig. 3: Savitzky-Golay smoothing, 4 additional hours of data points for each end.

different window sizes. The smaller window size reveals some details such as the drop in activity between noon and 1PM (lunchtime), while the larger window size is detailed enough to show that daytime is more active than nighttime. This filter performs well mainly for the center of the data set. The edges of the smoothing are clearly inaccurate, especially the sudden rise at the end of the day. This is a known issue with this filter. Luckily we usually also have the data of the preceding and following day. By starting the smoothing earlier and ending it later, we obtain a better smoothing. Figure 2 was generated using the data starting at 11PM the day before up to 1AM the day after. In figure 3 we increased this margin to 4 hours at each end. While the 1 extra hour does little to improve the smoothing and even leads to a worse result in one case, the effect disappears completely with the 4 additional hours. We use this 4 hour buffer for all smoothings. Furthermore we decided to use the larger window size, as we noticed plots with multiple days combined were more readable with this size. Additionally effects such as the drop during lunchtime were often not seen even with tighter window sizes.

Using an adapted version of Simon Wünderlich's FFT_eval code, Python's Matplotlib library, the mathematical formulas mentioned above and a Savitzky-Golay filter with window size 361 we graphically represent our data points per node. For one week (Monday 15 May - Sunday 21 May) we plot each day's smoothing, for easy comparison between the days. We repeat this for multiple channels in both bands. Each color in the plot represents a day of the week, using the legend in figure 4. All other plots use the same legend, although days may be missing.

Fig. 4: Legend: days of the week

3.1 Accuracy of the measurements

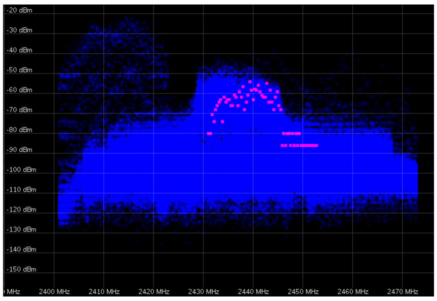

Fig. 5: 2.4 GHz spectral scan with active nearby device at 2.437GHz.

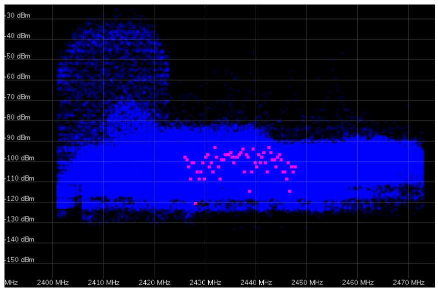

Fig. 6: 2.4 GHz baseline spectral scan.

We first confirm that the spectral scan does in fact accurately measure activity per channel. To test this, we performed a data transfer with a laptop positioned roughly 50cm from the node, using available 2.4 GHz and 5 GHz networks. The 2.4 GHz network was using channel 6 (around 2.437GHz) and lead to the spectral scan in figure 5. This scan shows a clear peak centered around channel 6 of around 20MHz wide. Figure 6 shows a scan of the same node around the same time, but with our data transfer disabled. While the hazy peak around channel 1 is still there, the peak around channel 6 is not visible, indicating it was caused by our data transfer. Comparing the two, we see that our data transfer caused an increase in received signal strength of around 40dBm.

Our 5 GHz test was using an access point centered around channel 132 (5.66GHz) and lead to figure 7. Compared to the flat figure 8 captured with the data transfer disabled, the peak is again very clear. Received signal strength is increased by up to 50dBm in this case. The scan is detailed

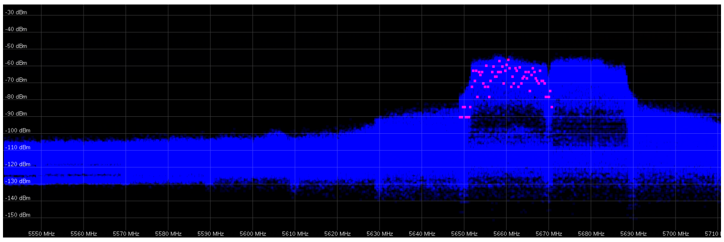

Fig. 7: 5 GHz spectral scan with active nearby device at 5.660GHz

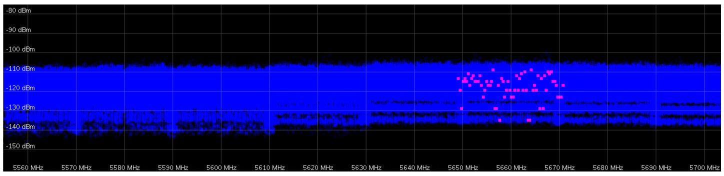

Fig. 8: 5 GHz baseline spectral scan.

enough to indicate that the access point was using a 40MHz wide channel: data is being transferred both in channel 132 (5.66GHz) and channel 136 (5.68Ghz). These two tests clearly show that this method is accurate enough for our goals.

4 Results

In this section we present the results of our experiment. Due to (presumed) hardware failure, some measurements failed. As a result we had to limit and/or shift the timeframe of the presented measurements for some nodes. This is indicated below.

4.1 2.4 GHz band

4.1.1 Recurring patterns between days

On the different nodes we had varying degrees of success in finding recurring patterns. In the 2.4 GHz band, two nodes that clearly showed repeating patterns across several days were node 8 at the Museum Plantin-Moretus and node 12 at the University of Antwerp, Middelheim campus. Both of these nodes detected patterns, with node 8 detecting a large increase in spectrum usage in the afternoon and node 12 detecting an increase during the daytime on weekdays. There were no peaks during the weekend. Node 8 was one of the failing nodes, so we had to limit its timeframe.

The most noticeable peak for node 12 is on channel 1 in figure 9, with the received signal strength during the daytime being up to 20dBm higher than during the night time. During the weekend (black and yellow) there is no peak whatsoever. This indicates the activity is most likely caused by

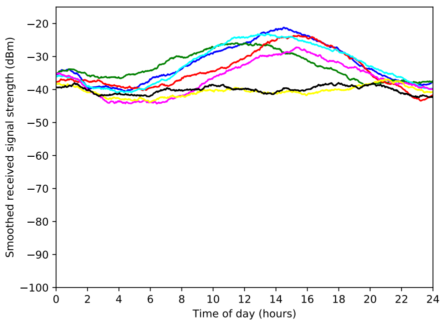

Fig. 9: Node 12, ch. 1, 15/05 - 22/05

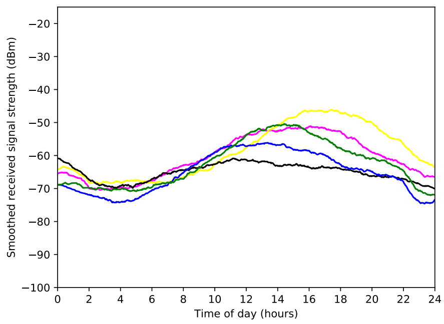

Fig. 10: Node 8, ch. 1, 12/05 - 16/05

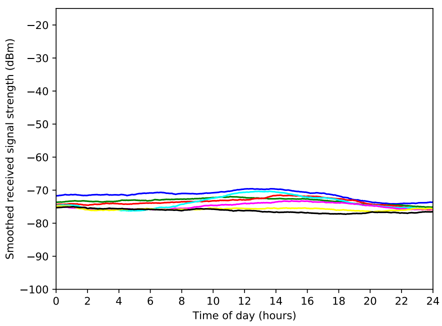

Fig. 11: Node 12, ch. 6, 15/05 - 22/05

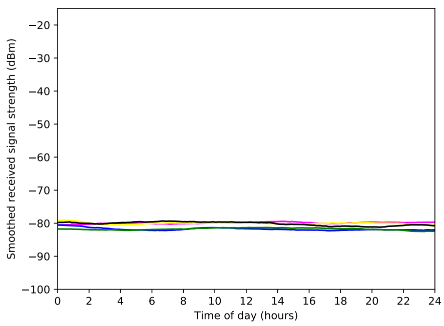

Fig. 12: Node 8, ch. 6, 12/05 - 16/05

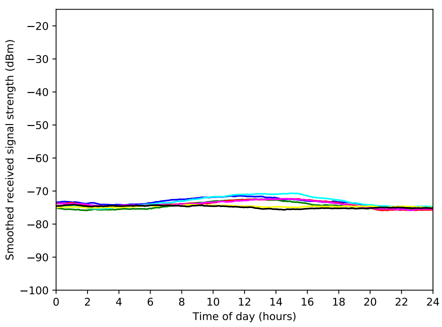

Fig. 13: Node 12, ch. 11, 15/05 - 22/05

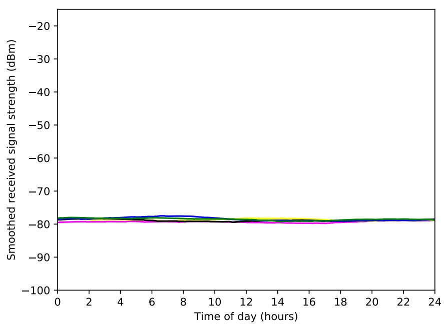

Fig. 14: Node 8, ch. 11, 12/05 - 16/05

Wi-Fi usage at the university, which is closed during the weekend. For the other channels there a noticeable peak during the daytime for some but not all weekdays. The weekend is still the quietest time of the week. Node 8 also shows a peak during the afternoon for channel 1 in 10, except on Sunday. Surprisingly the museum is open on Sunday, but closed on Monday. Of the days with a peak, Monday's peak is the lowest. This seems to indicate that while visitors at the museum have some effect on the overall signal strength, the peak has another source, possibly an office nearby.

We found no such peaks for any other nodes: spectrum usage was stable throughout the day. In the following section we investigate how active the different channels are.

4.1.2 Channel activity

As shown in figures 15 to 20, channel 1 is usually the busiest channel in the 2.4 GHz band, with channels 6 and 11 trailing far behind. Node 3 and 9, shown in those figures, measure a very busy medium around channel 1. However channels 6 and 11 are not particulary busy compared to other nodes. The two nodes show channel 1 activity of over -25dBm. This is likely caused by something else than a Wi-Fi router, although we are not sure what. This would likely make communication with the node over channel 1 very difficult.

All nodes covered so far were indoors nodes. We had access to one outdoors node, node 1, on which we also performed the experiment, as seen in figures 21 to 23. On the indoors nodes we noticed that channel 6 and 11 were never any busier than channel 1. This is also true for node1: while activity is fairly constant throughout all tested days, channel 1 is again the busiest. Note that we again do not have a full week's data for this node. There is a remarkable difference between weekdays and the weekend here. For channel 11, the weekend is more quiet, however for channel 6 the weekend is the busiest period.

4.2 5 GHz band

4.2.1 Recurring patterns between days

The data gathered during the 5 GHz measurements proved to be less interesting than the data we gathered in the 2.4 GHz measurements. Most of the channels we measured turned out to be silent or contain very little signal. This is partly to be expected. Many common communication devices only use the 2.4 GHz frequency band and many routers in use do not yet support the 5 GHz band. Furthermore, any communication that does occur in this band can be more spread out as the band is a lot wider than the 2.4 GHz band. For the most part, the channels that did show activity did not

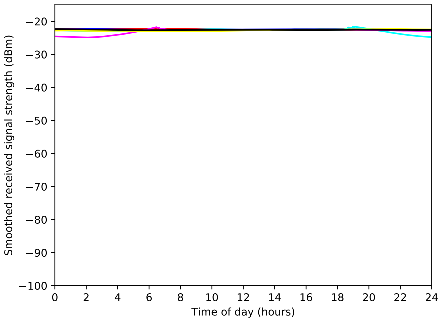

Fig. 15: Node 3, ch. 1, 15/05 - 22/05

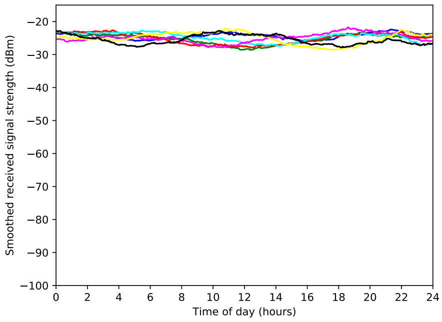

Fig. 16: Node 9, ch. 1, 15/05 - 22/05

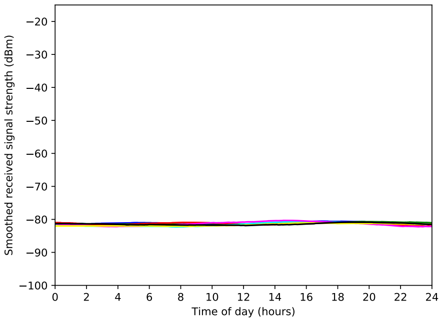

Fig. 17: Node 3, ch. 6, 15/05 - 22/05

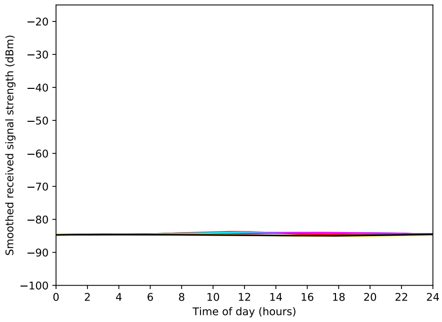

Fig. 18: Node 9, ch. 6, 15/05 - 22/05

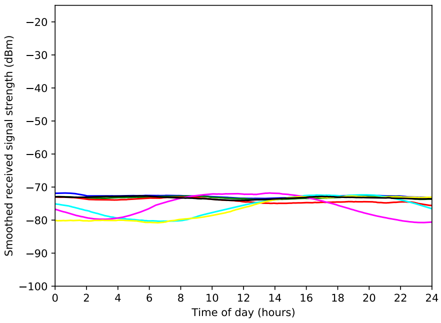

Fig. 19: Node 3, ch. 11, 15/05 - 22/05

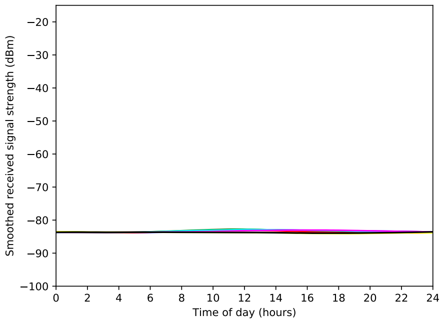

Fig. 20: Node 9, ch. 11, 15/05 - 22/05

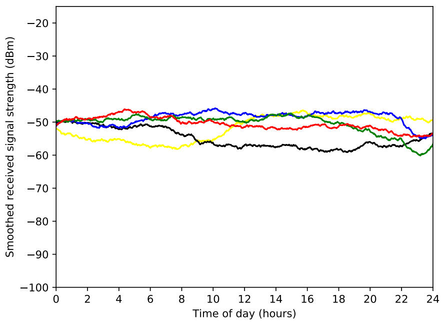

Fig. 21: Node 1, ch. 1, 13/05 - 17/05

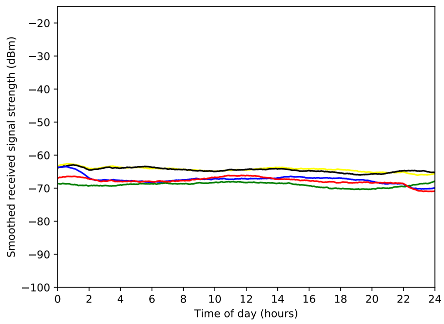

Fig. 22: Node 1, ch. 6, 13/05 - 17/05

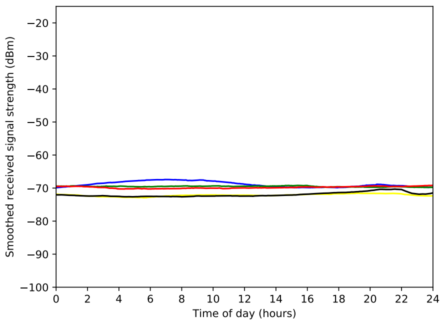

Fig. 23: Node 1, ch. 11, 13/05 - 17/05

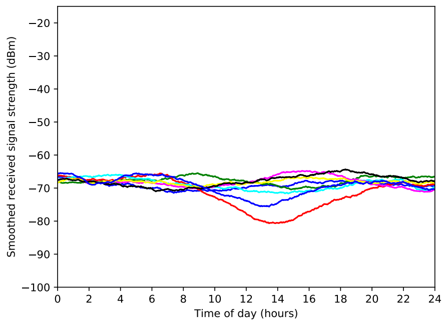

Fig. 24: Node 3, ch. 36, 15/05 - 22/05

show any significant patterns or recurring phenomena. In most cases the received signal strength was very stable on all channels. We did notice some remarkable behaviour though. For example, node 3 measured a lower signal strength for some time around noon on both May 17th and May 22nd on channel 56, in figure 24. The reason for this however is not as clear as with the daily peaks experienced in the 2.4 GHz It might be that the decrease occurs every couple of days, for example due to a router switching channels temporarily. It could also simply be an anomaly. For this node, channel 36 was the only somewhat active channel. All other channels saw barely any activity in the 5 GHz band.

It is worth noting that, apart from channel 36, there is some difference in the stability of the received signal between the outdoor node and the indoor nodes. The outdoor node has at least some activity on every channel whereas most of the indoors nodes show the bare minimum of activity for most channels. An example of the outdoors node's activity on channel 56 versus an indoors node on that same channel is shown in figures 25 and 26. There could be some outside source of slight intermittent interference. As we only had access to one outdoors node we cannot determine whether this generally occurs with outside nodes, or is specific to this one.

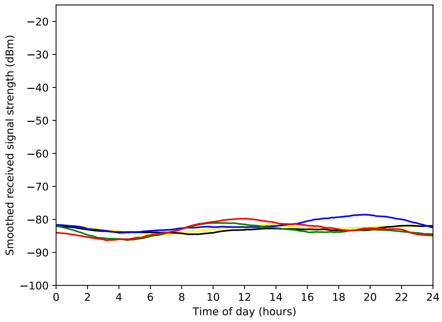

Fig. 25: Node 1, ch. 56, 13/05 - 17/05

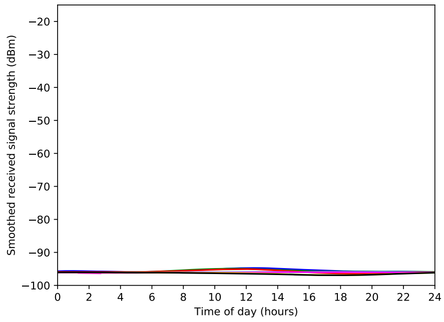

Fig. 26: Node 9, ch. 56, 15/05 - 21/05

There were some other interesting phenomena we observed in the 5 GHz channels. For example, node 6 shows a sudden drop in activity on both channels 56 and 64, coinciding with an increase in activity on channels 112 and 120, as seen in figures 27 to 30. Looking at a random spectral scan from before and after the shift, we indeed see the same behaviour. There was clear activity in channels 56 and 64 before the shift, seen in figure 31. While

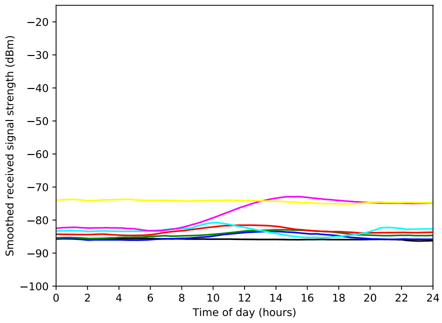

Fig. 27: Node 6, ch. 56, 14/05 - 20/05

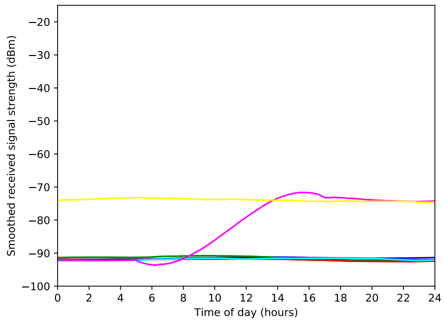

Fig. 28: Node 6, ch. 64, 14/05 - 20/05

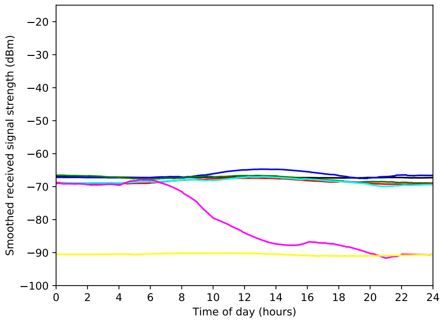

Fig. 29: Node 6, ch. 112, 14/05 - 20/05

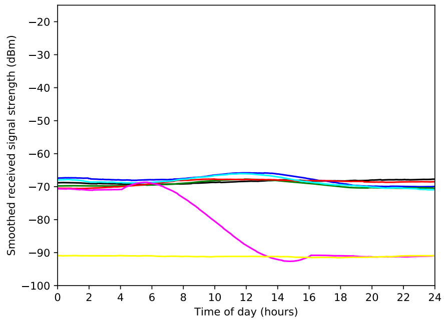

Fig. 30: Node 6, ch. 120, 14/05 - 20/05

there is some very slight activity in channel 60, so few samples contained any trace of it that it was filtered out. Later on, figure 32 shows that

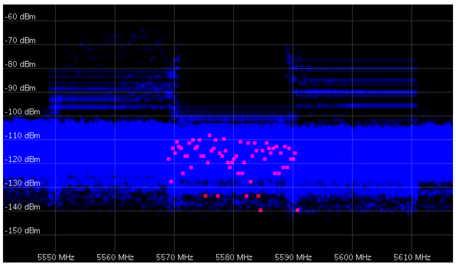

Fig. 31: Node 6 channels 56-64, before shift

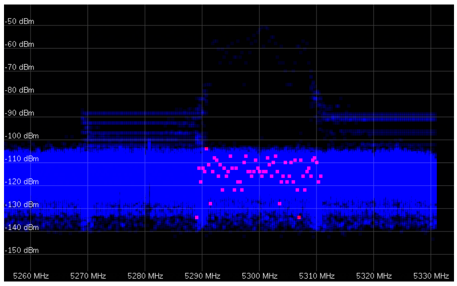

Fig. 32: Node 6 channels 112-120, after shift

this activity signature has moved to channels 112 and 120, now with the channel in between showing no activity at all. We are not sure what device exactly causes this, but it is clear that it was at some point switched to another channel. This shows that the activity in a channel can change at a moment's notice, and indicates that scheduled or even constant monitoring of the spectrum is not without merit. We do note that the received high signal is still only -70dBm, meaning there is still room for communication. Furthermore the spectral scan samples show that the affected channels are still silent for a large fraction of the time.

4.2.2 Channel activity

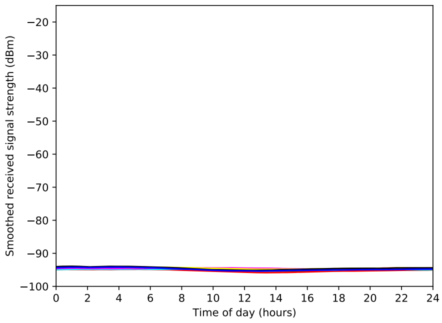

Fig. 33: Node 3, ch. 120, 15/05 - 22/05

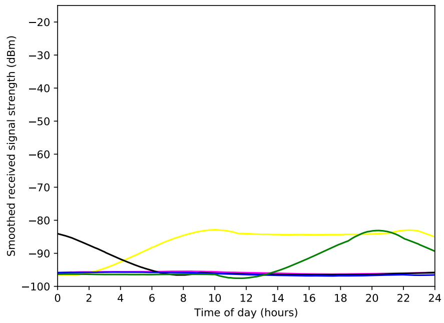

Fig. 34: Node 8, ch. 120, 12/05 - 16/05

For all nodes except 1 (outdoor), 6 and 8, channels 100 and above seem to contain no activity. For the outside node this could merely be some outside interference, although more outside nodes are required to confirm this. For the other two nodes this might simply be a nearby 5 GHz router. Even for those nodes channels 100 and up are fairly silent. Figures 33 to 35 show activity on higher channels for nodes 3, 8 and 1. Each of these was somewhat busy on the 2.4 GHz band, and showed some activity on the lower 5 GHz channels. In the higher channels they barely exceed -80dBm.

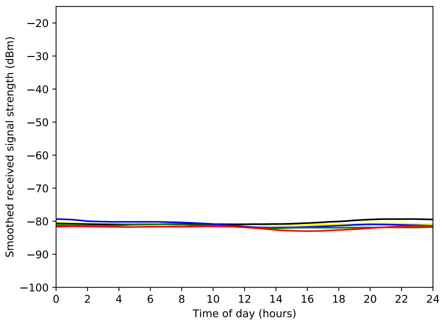

Fig. 35: Node 1, ch. 140, 13/05 - 17/05

We do again notice shifts in signal strength with node 8, most likely caused by devices hopping to another frequency.

For the lower channels, i.e. channels between 36 and 64, some more activity is observed: mainly channel 36 and occasionally channel 56 are somewhat used. Channel 36 is constantly active on nodes 3 and 1 (outside), as seen in figures 36 and 37. Furthermore channel 56 shows clear daytime peaks except during the weekend in figure 38, likely indicating Wi-Fi usage. Channel 40 is in all cases silent, one example being shown in figure 39. Here we do note a peculiarity of the spectral scan at channel 40. Each node, except for the outside node, consistently shows the pattern in figure 40. It seems that every inside node always measures this slight peak, but it is completely absent for the outside node. As all inside nodes are identical hardware-wise, but the outside node is not, we suspect some component of the inside nodes is continuously creating a signal on channel 40.

4.3 Implications of high signal strength

A high or unstable measured signal strength does not necessarily make a channel unusable for a City of Things node. First of all, we note that all received signal strengths previously reported were due to activity caused by external sources (as opposed to by the node itself). When considering using the node for communication, all those signals are considered as noise. As long as this noise is lower than the signal strength used for the node's communication, there is no issue. While a constant noise of -20dBm will make communication very difficult, noise of -70dBm, -60dBm or even -50dBm should be no problem for close-range communication, as the node and its peer could probably generate a stronger signal. Furthermore it is important to note that in many cases the measured high signal strength was not constant. As it was probably caused by a communication device (likely Wi-Fi), the signal source remains silent for a significant fraction of the time. Furthermore such sources of potential interference probably implement some

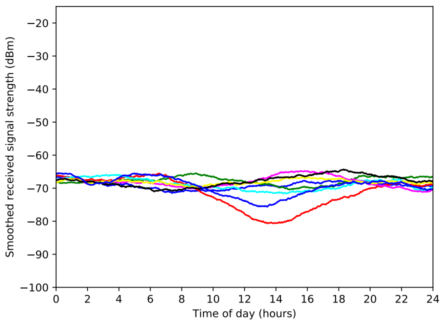

Fig. 36: Node 3, ch. 36, 15/05 - 22/05

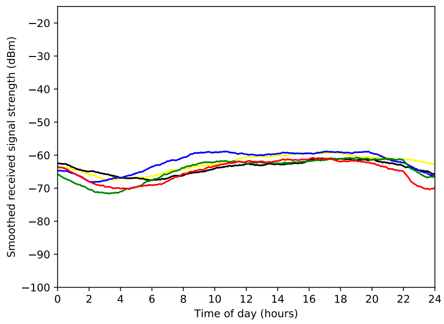

Fig. 37: Node 1, ch. 36, 13/05 - 17/05

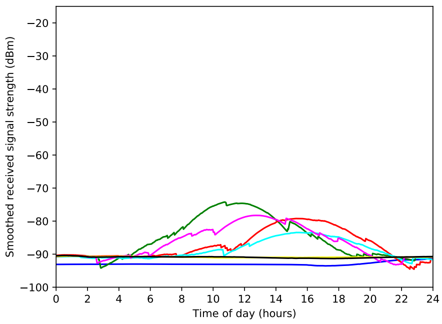

Fig. 38: Node 12, ch. 56, 15/05 - 22/05

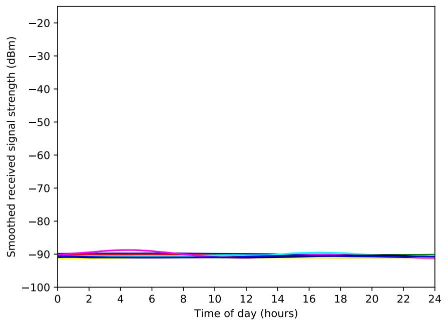

Fig. 39: Node 10, ch. 40, 15/05 - 22/05

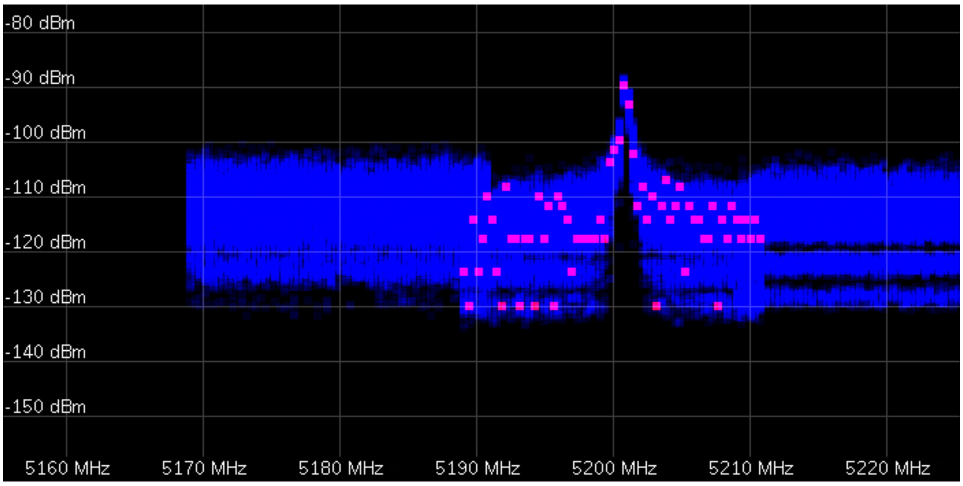

Fig. 40: Spectral scan: peak for channel 40

sort of listen-before-talk, further facilitating communication with the node in the presence of such sources. It is however difficult to predict exactly how well communication will work for a specific situation without actually trying it out.

4.4 Validation

While there is no official confirmation from the chip manufacturer that our interpretation of the spectral scan data is correct, we are confident that our interpretation gives at least a solid estimation of spectrum activity. First of all the experiment in section 3.1 shows that when we add a source of RF activity near the node, this is clearly seen in the spectral scan at exactly the right frequency.
Furthermore we discovered daily patterns where we expected them. The Middelheim offices are busy during the daytime on weekdays but fairly silent during the weekends and nights. While not shown in the plots above, holidays were just as quiet as weekends.

5 Conclusions

In this report we presented our findings on activity in the RF spectrum in the 2.4 GHz and 5 GHz bands in the city of Antwerp. One clear theme in our results is that the 5 GHz is overall quieter than the 2.4 GHz band. This is not surprising. The 5 GHz band is a lot wider than the 2.4 GHz band, and its signals do not carry as far. Furthermore, assuming that a lot of interference originated from Wi-Fi routers, one factor could be that many active routers and other devices do not yet support 5 GHz. In addition, technologies such as Bluetooth, which could also be creating signals, only affect 2.4 GHz.

In some environments we notice a daily pattern where the signal strength is about 20dBm higher during the day compared to the night. As this was mainly observed on nodes in office spaces, this effect disappeared during the weekend. Other nodes show absolutely no difference between daytime and nighttime. Often this is when the spectrum is just very quiet. One interesting observation is that channels 6 and 11 were never busier than channel 1. Furthermore, we found nothing indicating that City of Things network would experience considerable interference in the 5 GHz band, especially for the higher channel numbers. When operating on the 2.4 GHz band we observed more activity that could, in some places and on some channels, hinder communication with faraway hosts. However there was always at least one channel fairly silent and thus usable.

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