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WiFi Performance
Netherlands 2017

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INHOUDSOPGAVE

MANAGEMENT SAMENVATTING

In 2014 heeft Agentschap Telecom Strict en FIGO opdracht gegeven voor een research project naar het gebruik van de 2.4 GHz en 5 GHz vergunningsvrije banden. Deze banden worden intensief gebruikt voor WiFi internet toegang in publieke en private omgevingen. Agentschap Telecom heeft in 2017 Strict en FIGO gevraagd om de metingen te herhalen voor trendanalyses maar ook voor een beter begrip van het gebruik van deze banden.

In het research project uit 2017 is ook onderzoek gedaan naar het gebruik van mesh-technologie, DFS kanalen en de effectiviteit van informatie campagnes en zijn WiFi router merken en types geanalyseerd. Naast de eerdere meetlocaties zijn 20 meetlocaties toegevoegd in Utrecht, in het stadscentrum en straten met rijtjeshuizen.

Alle metingen zijn uitgevoerd door gebruik te maken van dezelfde meetmethodieken en apparatuur als in 2014. De exact identieke 183 locaties zijn opnieuw bezocht en dezelfde testen zijn uitgevoerd. Op basis van het onderzoek zijn de volgende conclusies getrokken:

- Er is een **duidelijke verschuiving van Access Points (APs) van de 2.4 GHz naar de 5 GHz band**. Tussen 2014 en 2017 is het gemiddeld aantal APs gemeten in de 5 GHz band toegenomen met ongeveer 200%.
- Er is een **enorme groei van 5 GHz APs in stadscentra.** Het aantal APs in de 2.4 GHz band bleef ongeveer gelijk, maar het aantal APs op 5GHz is waarschijnlijk ongeveer gelijk aan het aantal 2.4 GHz APs.
- In 2014 ondersteunden bijna alle APs de langzaamste datasnelheden (802.11b), terwijl in 2017 ongeveer **een derde van de gemeten APs alleen hogere datasnelheden ondersteunen** (802.11g/n). Dit verbetert de beschikbare doorvoer, terwijl ook de interferentie voor APs in de omgeving wordt verlaagd vanwege het kleiner bereik van 802.11g/n.
- De metingen laten een **significante verlaging van het aantal APs** zien ten opzichte van 2014. Er wordt aangenomen dat dit een direct effect is van de verandering van beacons van de langzaamste datasnelheid (802.11b) naar een hogere datasnelheid (802.11g/n), aangezien de hogere datasnelheid van beacons leidt tot een kleiner bereik, en daarmee minder zichtbaarheid.
- Over het geheel van alle metingen in de 2.4 GHz band is de **WiFi datadoorvoer lichtelijk verbeterd**. Toch zijn er nog veel locaties met extreme congestie, met name in stadscentra.

Enkele aanbevelingen zijn gemaakt voor toekomstige meetprojecten. Voor WiFi gebruik gelden de volgende aanbevelingen:

- De impact van beacons op 2.4 GHz blijft groot, omdat ze vaak door elke AP worden uitgezonden en een significant deel van de beschikbare capaciteit gebruiken.
- Achterwaartse compatibiliteit met een oude en relatief langzame WiFi standaard (802.11b) wordt nog steeds in veel gevallen geboden. Deze optie moet zoveel als mogelijk worden ontmoedigd, aangezien dit een negatieve impact heeft op de beschikbare capaciteit.

ABSTRACT

In 2014 Agentschap Telecom commissioned Strict and FIGO to execute research into the spectrum use of the 2.4 GHz and 5 GHz license exempt frequency bands. These bands are widely used for WiFi internet access in public and private areas. Agentschap Telecom commissioned Strict and FIGO to repeat and extend the measurements, both for trend analysis as well as a further understanding of the usage of these bands.

The 2017 measurements also included research into the use of Mesh-technology, DFS channels, the effectiveness of information campaigns and analysis of the WiFi router brands and types. In addition to the earlier measurement locations, also measurements were performed in Utrecht, another city with dense urban areas.

All measurements were performed using exactly the same measurement setup and equipment. The exact same 183 locations were revisited and the same tests were performed. Based on the research, the following conclusions were drawn:

- There is a **clear shift of Access Point devices from the 2.4 GHz to the 5 GHz band**. Between 2014 and 2017 the average number of APs measured in the 5 GHz band has increased by approximately 200%.
- There is a **huge growth of 5 GHz APs in city centres**. The amount of APs in the 2.4 GHz range remained roughly equal, but now the number of APs at 5GHz may be close to or equal to the number of 2.4 GHz devices.
- In 2014 nearly all APs supported the lowest data rate (802.11b), while in 2017 **roughly one third of the measured APs only support higher data rates** (802.11g/n). This improves the available throughput, while also decreasing the interference for neighbouring APs due to the shorter range of 802.11g/n.
- The measurements shows **a significant decrease in the number of APs.** It is assumed that this is a direct effect of the change of beacons at the lowest data rate (802.11b) to a higher data rate (802.11g/n), as the higher data rate of beacons leads to a smaller range, resulting in less visibility.
- The **overall WiFi throughput performance in the 2.4 GHz band is slightly improved.** This is expected to be due to the lower occupancy of the air interface. However, many locations still show severe congestion, in particular in the city centre environment.

Some recommendations are made for future measurement projects. With regards to WiFi usage the following remarks are made:

- The impact of beacons at 2.4 GHz remains large, because they are transmitted very often by every AP and use a significant amount of the available capacity.
- Backward compatibility to an old and relative slow WiFi standard (802.11b) still seems to be supported in many cases. This option should be discouraged as much as possible because this has a negative impact on available capacity.

1. INTRODUCTION

The Radiocommunications Agency Netherlands (Agentschap Telecom) has a public role as watchdog and expert for the efficient use of the radio spectrum. In 2014 Agentschap Telecom commissioned Strict and FIGO to execute research into the spectrum use of the 2.4 GHz and 5 GHz license exempt frequency bands, which are widely used for WiFi internet access in public and private areas [Ref 1]. Agentschap Telecom commissioned Strict and FIGO to repeat and extend the measurements, both for trend analysis as well as a further understanding of the usage of these bands.

1.1 Assignment

The Radiocommunications Agency Netherlands commissioned Strict and FIGO for a research project to investigate the risks of congestion and interference in the 2.4 GHz and 5 GHz frequency bands.
The goal of this assignment is threefold:

1. To repeat the measurements from 2014 and compare the results between 2014 and 2017;
2. To provide the Agency with the knowledge and expertise so that measurements can be repeated in the future;
3. Optionally to perform new measurements and/or analyses into the use of Mesh-technology, DFS, the effectiveness of information campaigns, extension of the measurement locations to other large cities and/or analysis of the WiFi router brands and types. All these questions are also covered in the research project.

The same measurement areas and the same indoor and outdoor measurement locations (all 183 in total) should be revisited. All the measurements should be repeated, especially focusing on:

1) Channel distribution of the measured access points;
2) Maximum throughput of data;
3) Provide an overview of the spectrum usage in both WiFi bands, regardless of protocol or technology.

The measurements should be performed during the same moments of the day as was the case in 2014:

- Public Areas in City centres: during opening hours, including evenings;
- Business Parks: during office hours;
- Residential Areas with high rises / flats / apartments: at the beginning of the evening;
- Residential Areas with houses in a row / semi-detached: at the beginning of the evening.

It is possible that since 2014 major changes have happened to certain measurement locations. All locations are visibly checked for changes since 2014, but no changes have been identified for the chosen locations. So no location needed to be excluded in comparison with 2014.

1.2 Strict and FIGO

This project was carried out jointly by Strict and FIGO. The project team consisted of the same people as for the previous License Exempt research project in 2014.

Strict Consultancy provides independent ICT advice with the focus on communication technology. Strict has extensive practical experience in the field of radio network analysis, especially related to the way it is used in business processes.

FIGO has a proven track record in research and development of radio communication systems, with focus on WLAN-systems.

The collaboration between Strict and FIGO provided an excellent basis for performing this research project. The combined experience was used in setting up the research, performing the measurements, analysis and reporting.

2. RESEARCH METHOD

2.1 WiFi Capabilities

To be able to interpret measurement information, it is important to understand the way WiFi works. WiFi is most often based on Access Points (APs) and clients, were clients use the APs to connect to the internet. Each WiFi transmission includes the MAC address of the transmitter. This must be unique within the communication range. Most WiFi APs use their universally unique factory default MAC address, this is used to identify individual WiFi APs.

WiFi uses a shared medium on the 2.4 GHz and 5 GHz bands. Each band has a number of channels. Figure 1 shows that in the 2.4 GHz band these channels are partly overlapping. Figure 2 shows that the 5 GHz band consists of sub-bands where three sub-bands are available in the Netherlands, and where starting at channel 52 Dynamic Frequency Selection (DFS) is required. The figure further shows the principle of channel bonding. E.g. a 40 MHz channel actually bonds two 20 MHz channels pairwise. This is also possible for 4 channels and 8 channels (160 MHz) for the latest WiFi standard like 802.11ac.

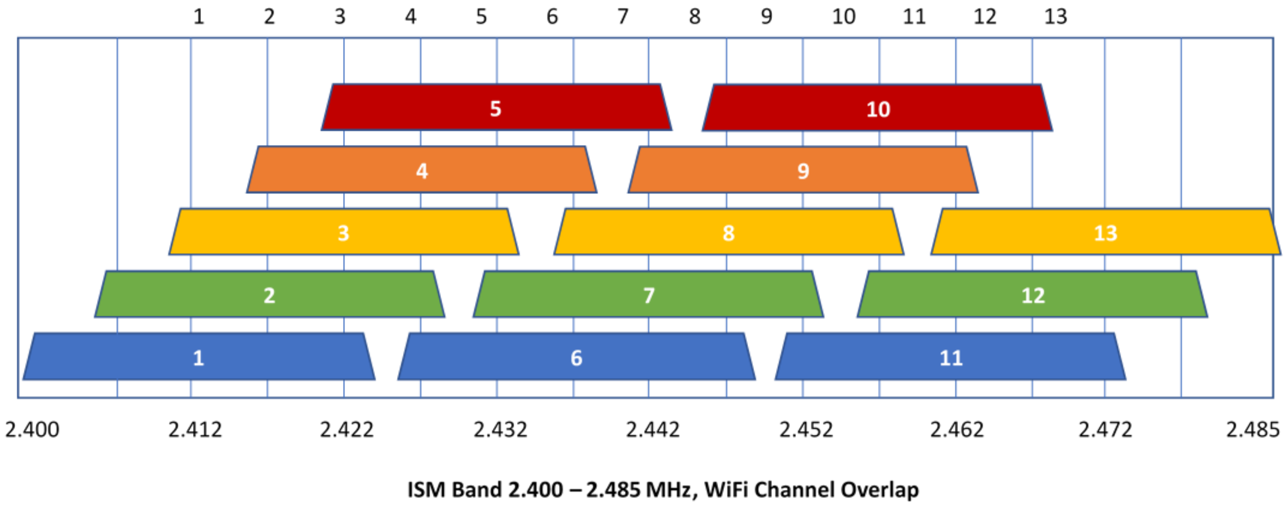


Figure 1 WiFi Channels in the 2.4 GHz band

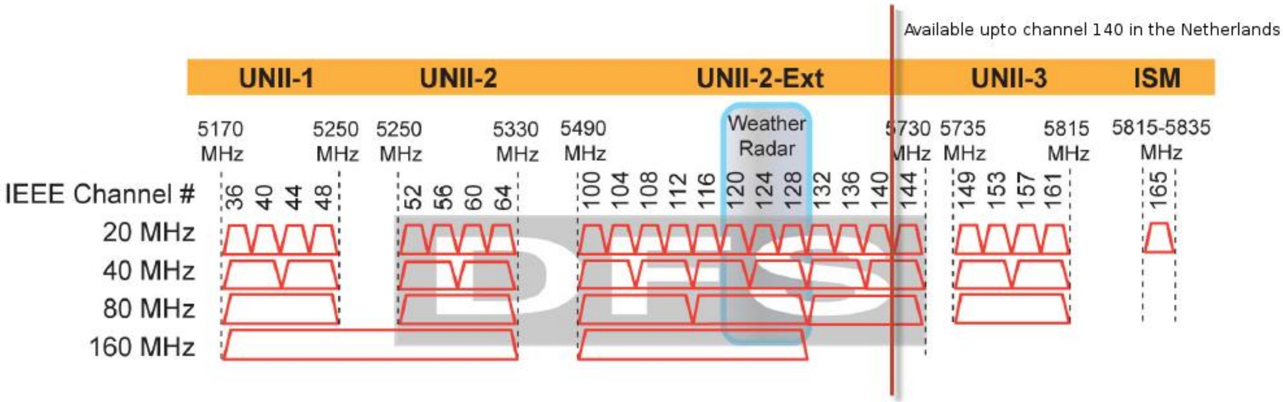


Figure 2 WiFi channels in the 5 GHz band

Most commonly, communication on WiFi data rates uses the maximum physical layer transmit rate, not considering protocol overhead. For the end-user, the maximum achievable throughput is however much more of interest. WiFi shows a significant difference between the achievable throughput in relation to the physical layer transmit rate.

Table 1 provides an overview of the 802.11 physical layer versions present in the 2.4 GHz and 5 GHz spectrum, with typical configurations and the resulting transfer rates and maximum throughput. This maximum throughput is what could be transferred between WiFi stations given maximum bandwidth is allocated, abundant signal strength is transferred and no other WiFi sources are active.

Table 1 Data rates for 802.11 products and standards [2], [3] and [4]

Standard	Configuration	Frequency (GHz)	Bandwidth (MHz)	Transfer rates (Mbps)	Max throughput (Mbps)
a	All	5	20	6 – 54	24
b	All	2.4	22	1 – 11	7.2
g	All	2.4	20	6 – 54	24
n	Low-end	2.4	20	7.2 – 72.2	51
	Mid-tier	2.4/5	20/40	7.2 – 288.8	210
	High-end		20/40	7.2 – 450	320
ac	Low-end	5	20/40/80/160	7.2 – 867	610
	Mid-tier			7.2 – 1730	1200
	High-end			7.2 – 2600	1800
	Ultra-high-end			7.2 – 3470	2400

This maximum throughput is significantly lower than the maximum transfer rate. The CSMA (Carrier Sense Multiple Access) of WiFi includes periods in which the system needs to be silent for executing Listen Before Talk (LBT) and transmitting physical layer acknowledgements. In addition, limitations due to chipsets and operating systems will reduce the achievable maximum throughput somewhat further.

Research thesis *Application-oriented Link Adaptation for IEEE 802.11* [2] calculates that CSMA reduces the theoretical maximum throughput for 802.11a/802.11g to 30 Mbps. Figure 3 is taken from this thesis and shows the measured maximum throughput in a test set-up for 802.11a for a given Signal to Noise Ratio (SNR). The maximum achievable throughput for 802.11a/g is 25 Mbps (3.1 Mbyte/s). Other sources state 23 Mbps [3] or 24 Mbps [4] as practical achievable maximum. The highest value measured in this research setup was 28 Mbit/s, realized in rural residential areas with very little spectrum occupancy using modern equipment.

Any WiFi physical layer is capable of transmitting on a variety of rates. High rates are good for throughput and efficiency, while low rates are good for range. Rate adaptation is an vendor specific automated process between AP and client, and estimates the SNR based on the packet error rate.

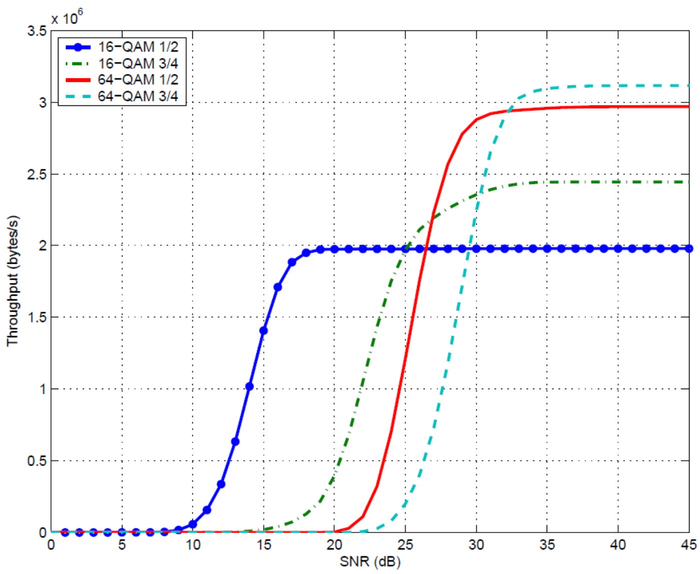


Figure 3 Maximum Throughput versus SNR for 802.11a

Considering 802.11n and 802.11ac, significant improvements are made in throughput, both with respect to the physical layer data rate and for the effective end-user throughput. Still similar limitations apply to 802.11n and 802.11ac, where the maximum throughput is much less than the peak transfer rate of the PHY layer.

The main improvements of the 802.11n and 802.11ac include MIMO (multiple special streams), a short guard interval (GI) and channel bonding (20/40 MHz for 802.11n and 20/40/80/160 for 802.11ac). What is achievable depends strongly on the configuration of the WiFi AP and clients. MIMO strongly relates to products being low-end or high-end, as each additional antenna for MIMO implies additional hardware. Channel bonding can provide higher throughputs in low-end and high-end products. Channel bonding is however not viable in busy environments, as it is only allowed when no interference is measured on all the used channels. When interference is measured, there is a fall back to the default 20 MHz. This implies that even though users configure channel bonding, many will not be able to use this in typical 2.4 GHz deployments.

WiFi APs transmit their beacon on the lowest rate they support, providing maximum range for their clients, and support of devices that are only capable on lower rates. A 2.4 GHz AP running in default settings transmits beacons at 1 Mbps when supporting both 802.11b and 802.11g/n, while it transmits beacons at 6 Mbps when supporting only 802.11g/n. Using advanced settings an AP can be configured to support only higher rates as minimum rate.

An AP backwards compatible with 802.11b will transmit its beacons and other signalling at 1 Mbps. This low speed signalling takes relatively more time in the air-interface, and therefore causes a heavy load, where traffic running at high rates using e.g. 802.11n causes much less load. The amount of air interface occupied by signalling is proportional to the number of APs visible, which grows to a high number in busy environments. So backward compatibility in support of legacy equipment is a major cause of reduced throughput.

Besides other WiFi networks, in particular the 2.4 GHz band is used by many other types of systems. The co-existence is governed by frequency hopping, spread spectrum or CSMA. Among various researches, the AT commissioned study *"Research into the Radio Interference Risks of Drones"* [5] clearly showed that WiFi is more susceptible to spread spectrum sources than vice versa. This is related to the basic regulation of the 2.4 GHz band. So when discussing the occupancy of the frequency band, the starting point needs to be "for whom". Within the scope of this research, the air interface occupancy is defined in relation to the amount of data a WiFi set-up can transfer.

Figure 4 summarizes that in a busy environment, WiFi legacy transmissions, other WiFi networks, and other radio sources (and so not ideal radio circumstances) reduce the achievable data rate, counteracting the improved data rate due to improvements in the standards.

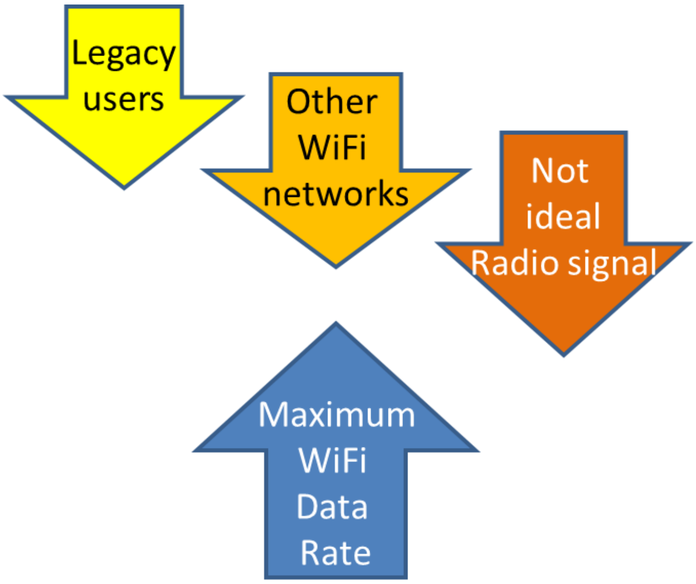


Figure 4 Impact on Maximum Data Rates

2.2 Research Methodology

The measurements are to a large extent a repetition of the measurements executed in 2014, therefore the basic measurement method is the same, which is described in detail in the 2014 report *"Research into the License Exempt Spectrum of the Netherlands"* [Ref 1]. As the current research is a follow-up of the 2014 research, the analysis is emphasized on the comparison over the two sets of measurements.

The aim of the research is provide a realistic view of the 2.4 GHz and 5 GHz frequency bands from the perspective of WiFi. The measurements and analysis addresses this through a set of measurements:

- Logging and analysis of the public information of WiFi signals present in the environment;
- Measurement and analysis of the achievable throughput in a standard WiFi AP and client set-up;
- Logging and analysis of the amount of WiFi and non-WiFi signal power present.

The measurements are executed consecutively, as parallel operation would cause mutual influence. Each set of measurements takes around 15 – 20 minutes.

The measurements take place at the day of the week/time of day that seems the most relevant to the measurements:

- Public Areas in city centres – during shopping hours including evenings;
- Business Parks with groups of companies – during office hours;
- Residential Areas (all types) – at the beginning of the evening.

2.3 Locations

The locations for the measurements are the locations of the 2014 research, extended with a number of urban locations. Existing locations are validated to ensure that changes of the physical environment are small compared to the previous measurements. No major changes were found in any of the locations.

The measurement campaign is extended by additional measurements in an urban environment. The 2014 measurement campaign included 183 locations. The 2017 campaign is enriched with 20 additional measurements at locations in the Utrecht urban environment, in both residential and city centre environments. Appendix A maps the locations.

The individual locations are grouped in areas. Per area 5-10 locations are defined, which are carefully chosen as typical examples. Table 2 shows the categories and subcategories of the locations.

Table 2 Categories of locations

1 City centre	a) Shopping Area	b) Shopping Mall	c) City centre
2 Business Parks	a) Outdoor	b) Indoor	
3 Residential, high-rise			
4 Residential, low-rise	a) Houses in a row	b) Semi-detached	

2.4 Representativeness

The measurements are executed at locations that are considered representative for the majority of typical WiFi usage, and at time instances that are typically the "busy hour". The measurement set is large enough for providing realistic generic insights and to perform trend analysis. The measurement set is however too small for highly accurate absolute statistics.

The majority of the measurements are executed outdoor, whereas the majority of the WiFi usage is indoor. Executing the measurements outdoor has an advantage in the ability to measure at a large number of locations, but may lack some accuracy with respect to the conditions the typical WiFi user experiences indoor.

Measuring outdoor however also is a good way to analyse the WiFi traffic leaking out of the buildings, and thereby potentially causing interference to one another.

2.5 Measurement Configuration

The measurement set-up in the 2017 measurements is the same set-up as used in 2014. The measurement setup consists of a combination of hardware and software. Figure 5 shows the physical set-up. The hardware consists of:

- WiSpy RF scanning unit
- 2 x Mobile Node running as AP (2.4 GHz + 5 GHz)
- Frame logger with 2 x WLAN radio (2.4 GHz + 5 GHz)
- Laptop
- Antennas, attenuators

The frame logger measures the presence of WiFi traffic, like visible APs, carriers in use, configurations and AP brand. The frame logger sniffs for visible WLAN packets, which are post-processed through parsing of the data to extract the information. The frame logger scans over the frequencies in both 2.4 GHz and 5 GHz bands. The WLAN radios are 802.11n radios, being capable of scanning and logging 802.11 a/b/g/n/ac packets.

The combination of laptop and the two Access Points is a set-up to measure the achievable throughput. The laptop connects to either AP running a throughput measurement, by trying to load the channel as much as possible. Both APs run each on a fixed frequency (2462 MHz (channel 11) / 5220 MHz (channel 44)). These channels are selected as not being the default channel, but a typical channel to be selected. The channels are fixed for reproducibility. During the measurements AP and client are at a predefined distance of 10 meters (this is measured with a laser). The AP signal is attenuated such that in a quiet environment the signal is just strong enough for a good quality link. This is a representation of a typical user, not very close to the AP, but clearly in range. With this tuning, the measurements will show a degradation of the throughput in the presence of other WiFi traffic.

The WiSpy unit is used for scanning the RF spectrum. WiSpy is a basic measurement tool, which provides a basic insight into the general spectral occupancy. This set-up focusses on assessing the technology independent spectral occupancy.

The stored data is analysed by using scripts. The 2014 scripts are extended in order to include the additional analysis of mesh networks. Analysis of DFS frequencies and measuring the manufacturers and types will be included by some limited modifications of the measurement scripts.

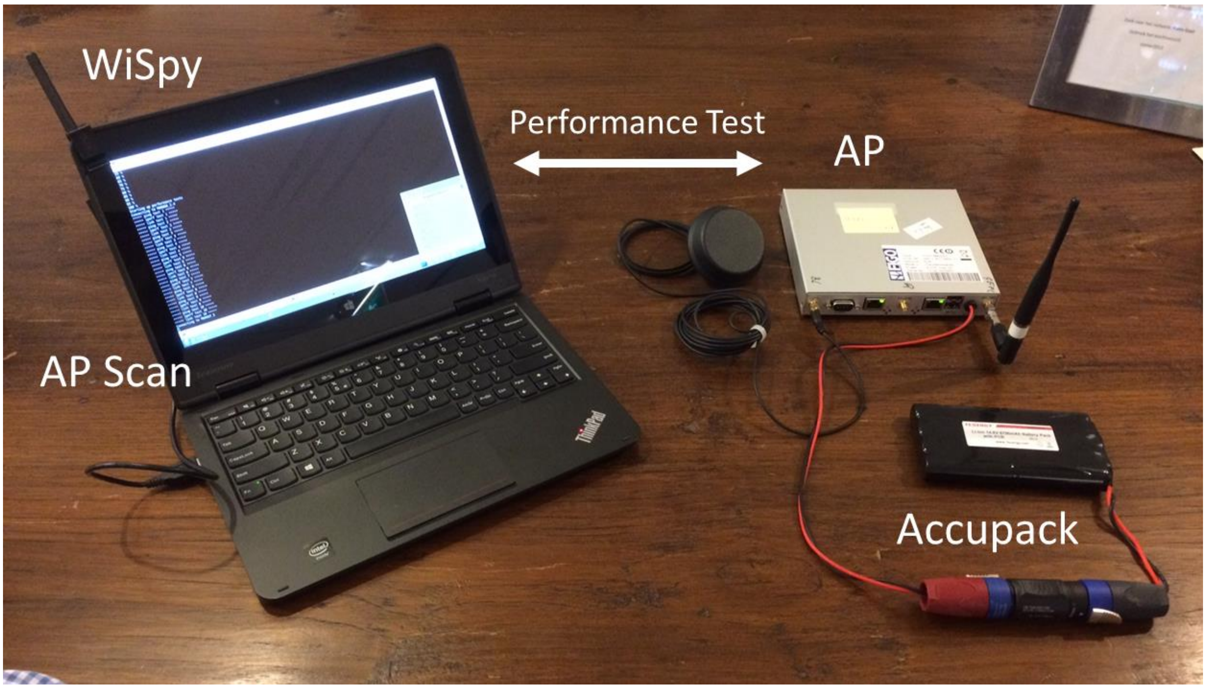


Figure 5 Overview of the portable test setup

2.6 Throughput Qualification

The performance of the WiFi connection is assessed through measuring the maximum achievable throughput in a predefined 802.11g and 802.11a link. The definition is chosen such that in a quiet environment, the throughput will be close to the maximum, while in a busy environment, the throughput will drop to very low values.

As indicated in section 2.1, a realistic maximum throughput for 802.11a/g is 23-30 Mbps. Interference and other WiFi traffic will reduce this throughput. In order to provide a better understanding of the effect of this reduced performance, the 2014 research qualified the throughput in four categories. Table 3 shows the qualification as used in both the 2014 and 2017 research. This qualification roughly indicates the user experience.

Table 3 Data Speed & Occupancy Qualification

Data speed	Qualification	User Experience
0 – 3 Mbit/s	Very Bad	Service degradation, problems with many services
3 – 6 Mbit/s	Bad	WiFi can be used for web browsing, problems with video applications
6 – 12 Mbit/s	Good	Most services work well
12 Mbit/s and above	Very Good	No problems expected, WiFi can follow higher internet access speed (cable modems, fibre)

2.7 Mesh networking

Mesh networking was also investigated in this project. However, mesh has no clear definition. In a more strict definition a wireless mesh network is a network topology with a rich interconnection between the connected devices. In such a network multiple routes exist between the devices, where the routes for the wireless traffic is negotiated among the nodes.

In a wider definition, the term mesh is frequently used as a means to identify the wireless extension of a wired infrastructure. The wireless mesh nodes act as repeaters, whereas the network topology is reduced to a tree or star structure. In publications these networks are also defined as having a spoke-hub structure, which is exactly the same.

In both cases, the practical advantage of a wireless extension of the network results in additional air interface traffic. For creating and maintaining the topology the nodes exchange additional control information. In addition, end-user traffic is transmitted once per hop, so multiple times.

As wireless mesh networking is not strictly defined, multiple methods for creating the network exist and are in use. The most well-known methods are:

- WDS (Wireless Distribution System): Intermediate nodes act as repeaters, in a star topology. The foreseen use is either bridging two networks or wirelessly extending a network. A device using WDS can be AP or client at the same time. So an AP serving clients can simultaneously be extended through a WDS repeater to serve other clients. WDS use is visible form the header.
- IBSS (Independent Basic Service Set): The devices run in ad-hoc mode and build their own network. All devices are peers. It creates a mesh with potentially multiple routes between nodes. A device running in IBSS mode cannot be AP or client simultaneously. Connecting clients requires a second radio in AP mode. This solution provides a pure backbone. The foreseen use is a standalone network. IBSS is visible from the header.
- MBSS (Mesh Basic Service Set) – 802.11s: All mesh devices are peers, like in IBSS, which may act standalone, and requires additional APs and clients for connecting with the outside world. In its typical implementation the physical devices can run MBSS simultaneously with being AP.
- Proprietary solutions on top of AP – client links: A mesh can be created while using normal AP – client links as a basis. Devices typically have multiple radios, to separate the backbone mesh from the access. E.g. solutions exist where the mesh is built as layer 3 routing protocol. These solutions are proprietary, and not visible through scanning as the links are observed as regular links.

WDS, IBSS and MBSS are all visible from the headers of WiFi packets. The use of these mesh modes is retrieved through post-processing of the data logged by the frame logger and is analysed in this research project.

2.8 Vendors

In order to be able to communicate WiFi devices in a single WiFi network need to have unique MAC addresses. The addressing can be either universal or local. Universal addresses are uniquely assigned to each device by the manufacturer. The first three octets identify the manufacturer and are known as the Organizationally Unique Identifier (OUI). Post-processing of the MAC addresses of the APs is used to generate the information on the vendors. For APs using a local MAC address (which is identical for all APs) it is impossible to identify the manufacturer.

3. RESULTS AND ANALYSIS

3.1 Introduction

This chapter discusses the results and analysis of the measurements. As the 2017 measurements are in the basis a repetition of the 2014, on the same locations with the same equipment, the main analysis is a comparison of the two sets of measurements.

The analysis is based on individual metrics in the measurements. Each section discusses one type of metrics, comparing the 2014 and 2017 results. Some of these analyses include processing of the data which was not done in this way in 2014. The raw measurement data of 2014 and 2017 are therefore processed anew.

For the 2017 measurements additional locations were added compared to 2014. The new locations in Utrecht are not included in the trend analysis, but are analysed separately in paragraph 3.9.

3.2 Number of APs observed

The measurements scan for unique APs in each environment. Figure 6 shows for all measurements in all locations the average number of APs per measurement. The figure compares the number of APs for the 2014 and 2017 measurements. In addition, the figure distinguishes between the 2.4 GHz, the non-DFS 5 GHz channels (36 – 48) and the DFS 5 GHz channels (52 – 140).

The figure clearly shows a shift of AP channels from the 2.4 GHz to the 5 GHz band. The average number of observed APs has increased in 2017 compared to 2014 by 15-20%. In this time period the observed number of APs in the 2.4 GHz band has decreased by roughly 10%, but the number of APs in the 5 GHz band has increased from roughly 10% to 30% of all APs observed. The number of APs active in the DFS frequency range is nearly equal to the number in the non-DFS range.

This change in the number of observed APs is not directly related to the number of APs in use. The reduction of the observed number of APs in the 2.4 GHz band is expected to be related to more beacons using a higher transmit rate, as will be discussed in section 3.4. A higher rate for a beacon results in a lower maximum range of the AP, and therefore in a smaller probability of being observed in these measurement. So it is not valid to conclude that the number of active APs has reduced. It is however valid to conclude that significantly less APs are present in radio range.

Likewise, as radio propagation is more easily obstructed at 5 GHz compared to 2.4 GHz, the range of 5 GHz APs is lower than for 2.4 GHz APs. As a result the probability of observing a 5 GHz AP is lower than for 2.4 GHz. So it is expected that the ratio of 5 GHz APs compared to 2.4 GHz APs in use is significantly higher than the ratio of the ones observed.

Due to a large variation in propagation conditions it is impossible to accurately identify the ratio between the number of APs in use at 2.4 GHz and 5 GHz. The measurement results however do suggest that the number of APs at 5 GHz are in the same order of magnitude as the number of APs at 2.4 GHz.

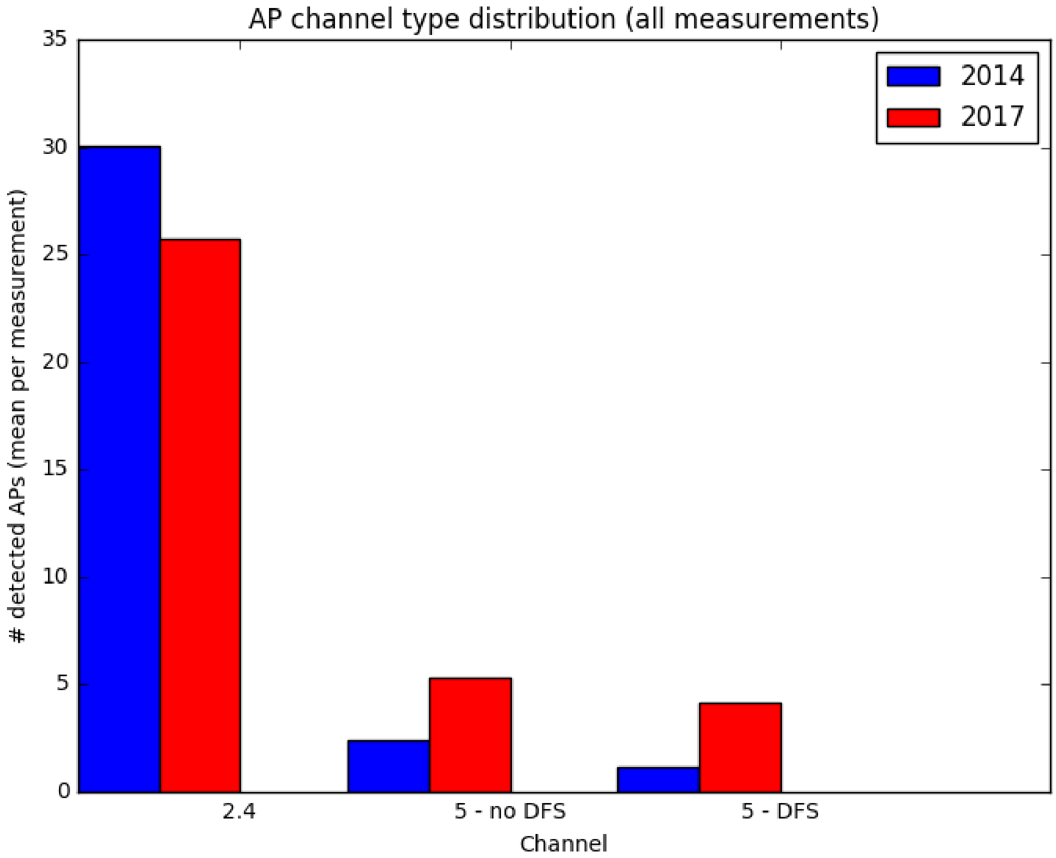


Figure 6 AP Channel type distribution

This observed chances in 2.4 GHz and 5 GHz is not equal for all environments. Figure 7 (next page) shows detailed results per environment type.

The business environment is a professional environment with rather limited WiFi traffic. The number of 2.4 GHz APs remains equal in 2017 compared to 2014. APs at 5 GHz represented already around 15% of all APs observed in 2014, and has increased to around 25% in 2017.

In the city centre, the number of APs in the 2.4 GHz range remained also nearly equal. With respect to the 5GHz band one can see that this frequency band represented nearly 25% of all APs observed in 2014, while in 2017 nearly 50% of all APs observed use the 5 GHz band. Considering that the visibility of APs at 5GHz is much less than at 2.4 GHz due to propagation conditions one may expect that the number of APs at 5GHz is in the same order of magnitude as the number using 2.4 GHz. APs using DFS frequencies are seen as frequent as using the non-DFS frequencies.

The residential areas show a very different result. The number of observed APs at 2.4 GHz in the high rise measurements has decreased by around 30%, and in low rise by 18%, when comparing 2017 to 2014. The percentage of observed APs at 5 GHz increased from 4% in 2014 to 19% in 2017 for both high rise and low rise areas. As indicated the remarkable reduction in 2.4 GHz APs is expected to be related to the change in beacon transmit range as discussed in section 3.4.

The number of observed APs at 2.4 GHz and 5 GHz summed has decreased for high rise by 17%. In low rise residential areas no significant change is observed in the overall number of APs.

The fact that less 5 GHz APs are observed in high rise is expected to be partly due to the less favourable radio propagation conditions for 5 GHz when measuring at ground level. As however also a relative low number of 5 GHz APs are observed in low rise residential areas, it is expected that the number of 5 GHz APs in residential areas is still significantly lower than the number of 2.4 GHz APs.

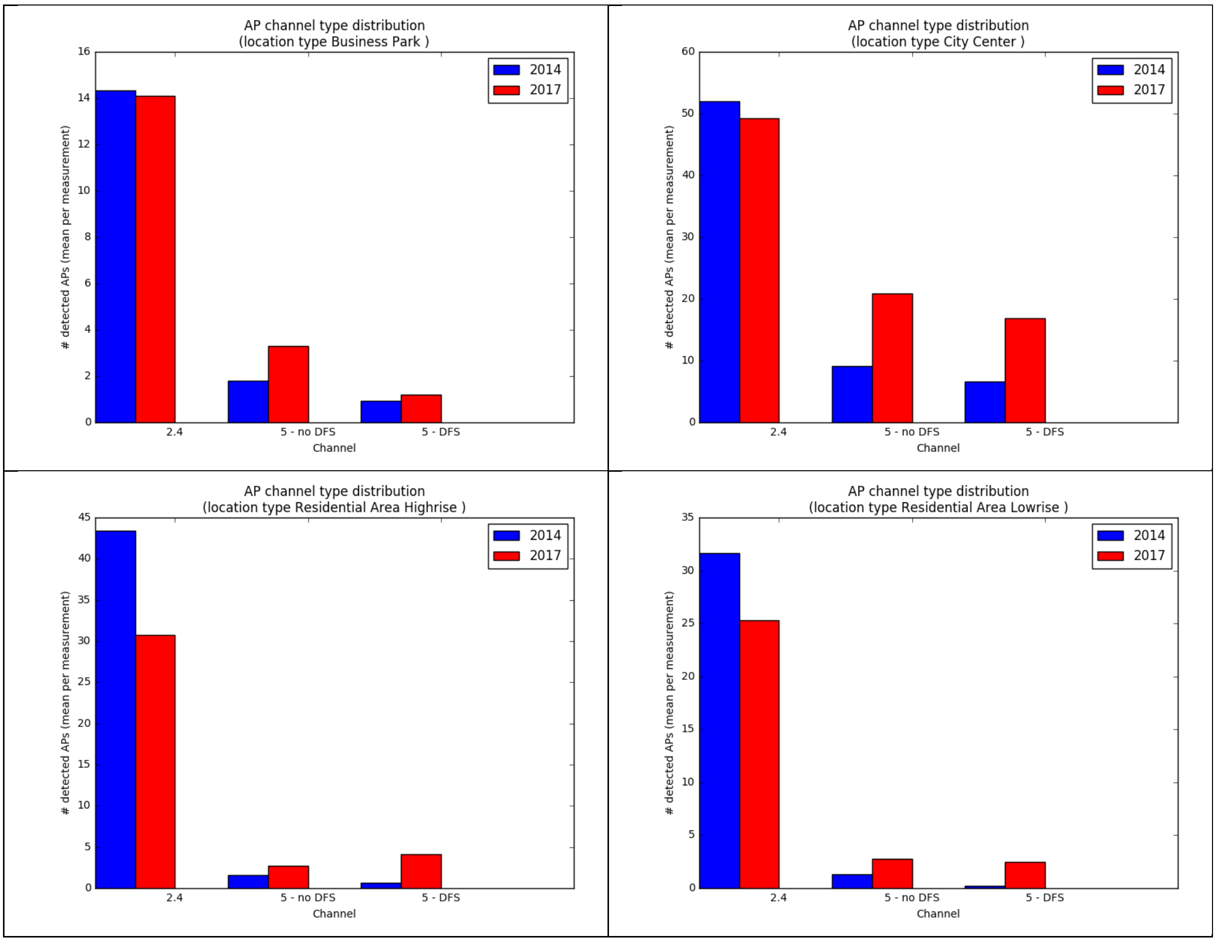


Figure 7 AP channel type distribution per environment

3.3 AP channel distribution

Figure 8 compares the AP channel distribution at 2.4 GHz for the 2014 and the 2017 measurements. Both in 2014 and 2017, channels 1, 6 and 11 are dominantly used. In 2014 67% of all APs were tuned to one of these channels, whereas in 2017 this percentage was reduced to 56%. Channels 1 and 11 are more popular than channel 6, in both 2014 and 2017.

Over the past three years there is a significant shift to channels 3, 4 and 13, although for business park environments this shift is less obvious.

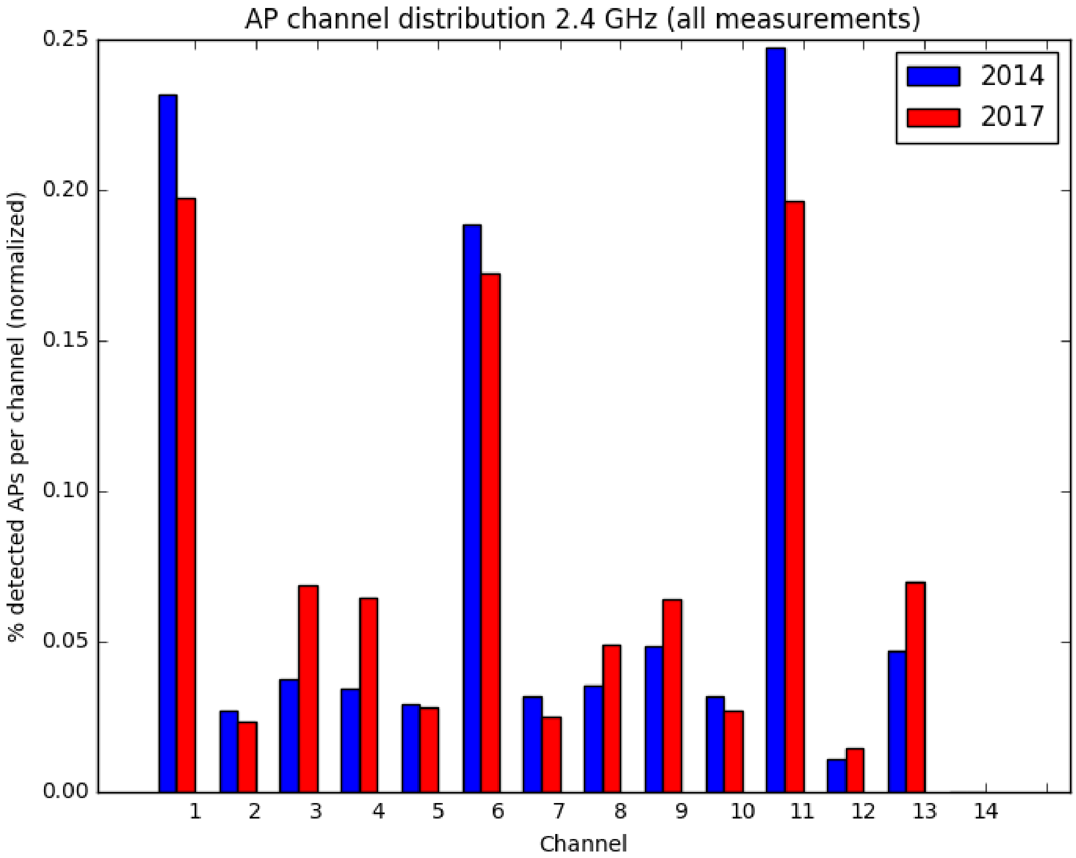


Figure 8 AP Channel distribution at 2.4 GHz

Figure 9 shows that the AP channel distribution is rather similar for the various environment types.

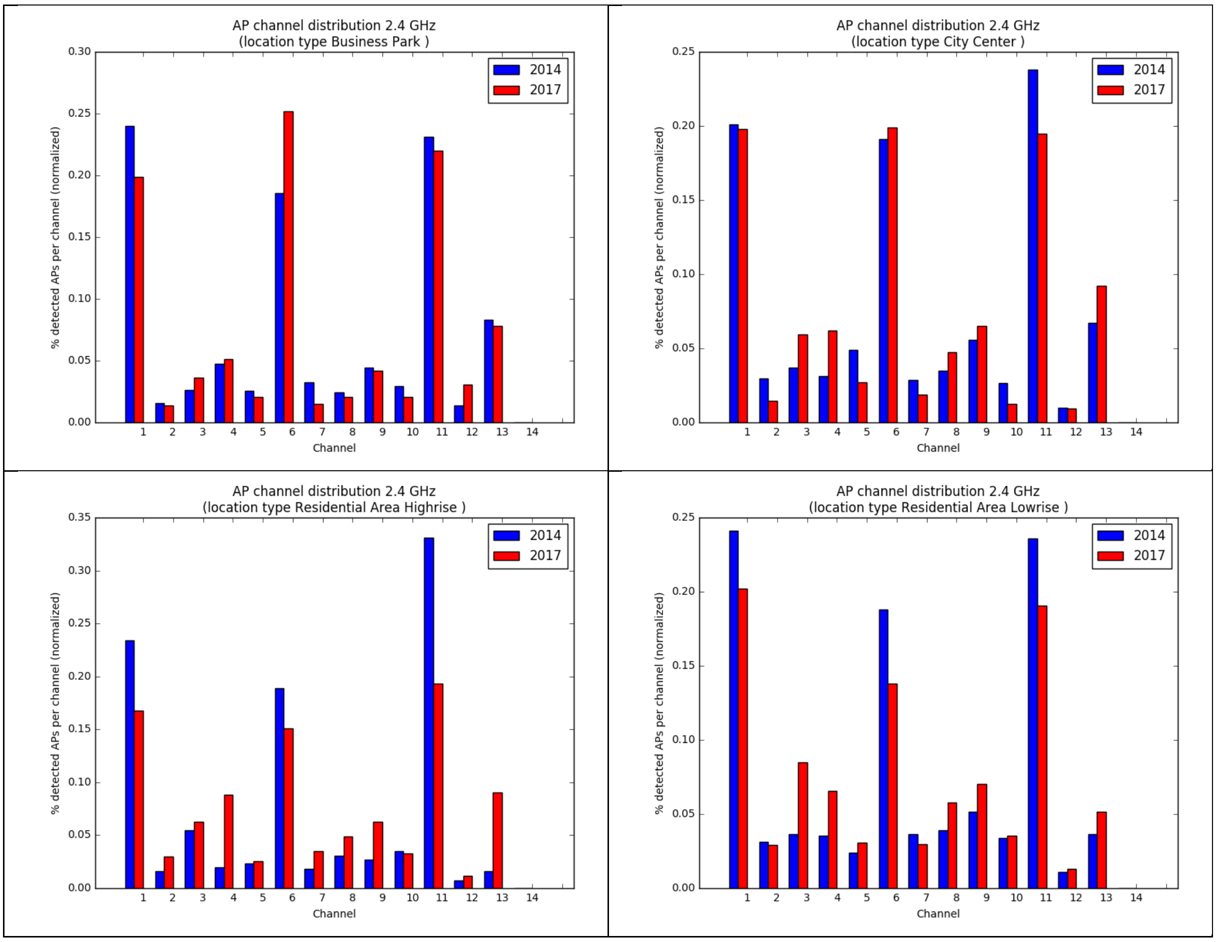


Figure 9 AP channel distribution per environment at 2.4 GHz

Figure 10 shows the AP channel distribution in the 5 GHz frequency range. With the increased use of 5 GHz, the selected AP channel also spreads out. Whereas in 2014, channels 36 (35%) and 44 (17%) are the dominant choice, in 2017 the dominant selected channels are 36 (17%), 44 (12%), 52 (11%) and 100 (13%).

The fact that channels 36, 44 and 52 are significantly more selected than the intermediate channels is expected to be related to the optional 40 MHz channel bandwidth introduced in 802.11n. Figure 2 (in paragraph 2.1) shows the channel bonding, bonding channels 36 and 40, channels 44 and 48, channel 52 and 56, etc.

Channels 52 and above require DFS. In 2014 just over 30% of all 5 GHz APs observed use DFS frequencies. In 2017 this has increased to nearly 50%. APs using channels 52 and 100 represent over 40% of all APs using the DFS frequencies. Channel 52 is the lowest channel in the UNII-2 band, and channel 100 is the lowest channel in the UNII-2 extended band. The high percentage using these channels suggests that many 5 GHz radios run these as default channels. There is also little need to change frequency as the interference is low. With a growing use of the 5 GHz band, a larger spread over the frequencies is to be expected.

Channels 120, 124 and 128 are hardly used. These frequencies overlap weather radar. This is an indication that DFS is effective in avoiding radar.

The differences in used channel distribution between the environments is considered non-significant. The still rather low number of 5 GHz APs observed, combined with the higher number of channels available in 5 GHz, makes that variation between environments relate to randomness of the sample.

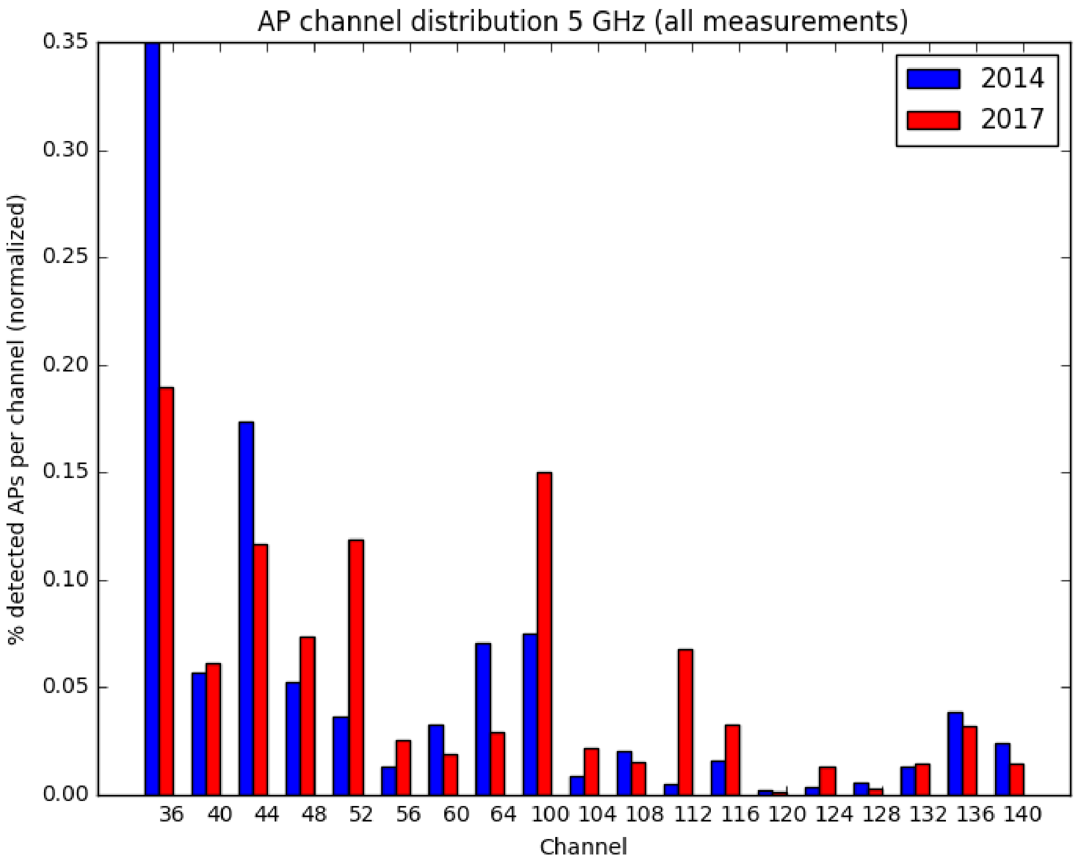


Figure 10 AP channel distribution at 5 GHz

Figure 11 shows the channel distribution for 5 GHz for the individual environments. The somewhat more even distribution in particular the city centre is related to the higher number of 5 GHz APs in this environment. Either frequency planning or automatic frequency selection results in a more even spread, due to the presence of other APs.

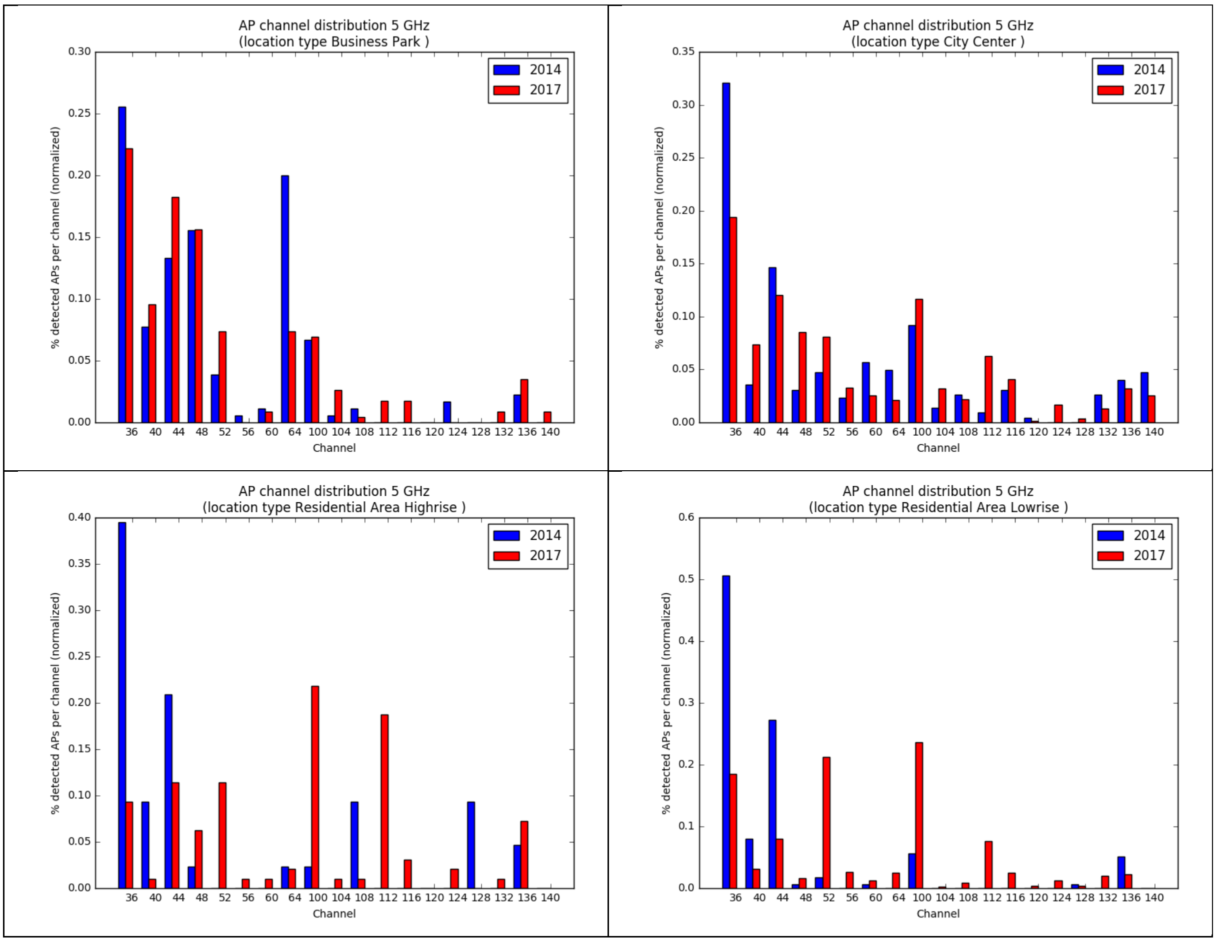


Figure 11 AP channel distribution per environment at 5 GHz

3.4 Rate distribution

The WiFi physical layer is capable of transmitting on a variety of rates. IEEE 802.11b supports the rates 1, 2, 5.5 and 11 Mbps. IEEE 802.11g/n support the rate 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. WiFi APs transmit their beacon on the lowest rate they support, providing maximum range for their clients, and support of devices that are only capable on lower rates. An AP running in default settings transmits beacons at 1 Mbps when supporting both 802.11b and 802.11g/n, while it transmits beacons at 6 Mbps when supporting only 802.11g/n.

Figure 12 shows the average number of detected beacon frames per measurements sorted by rate. For the analysis of this measurement, it should be considered that higher rates have less range, and are therefore less visible.

The figure shows that a significant shift has occurred in beacon rate setting from 1 Mbps to 6 Mbps, so from 802.11b to 802.11g/n. Assuming that the visible footprint of an Access Point is roughly inversely proportional to the beacon transmit rate, the number of APs running in 802.11b vs 802.11g/n mode can be estimated very roughly. One out of three APs run in 802.11g/n mode in 2017, while this was a negligible amount in 2014. In addition the figure shows that rarely other rates are found.

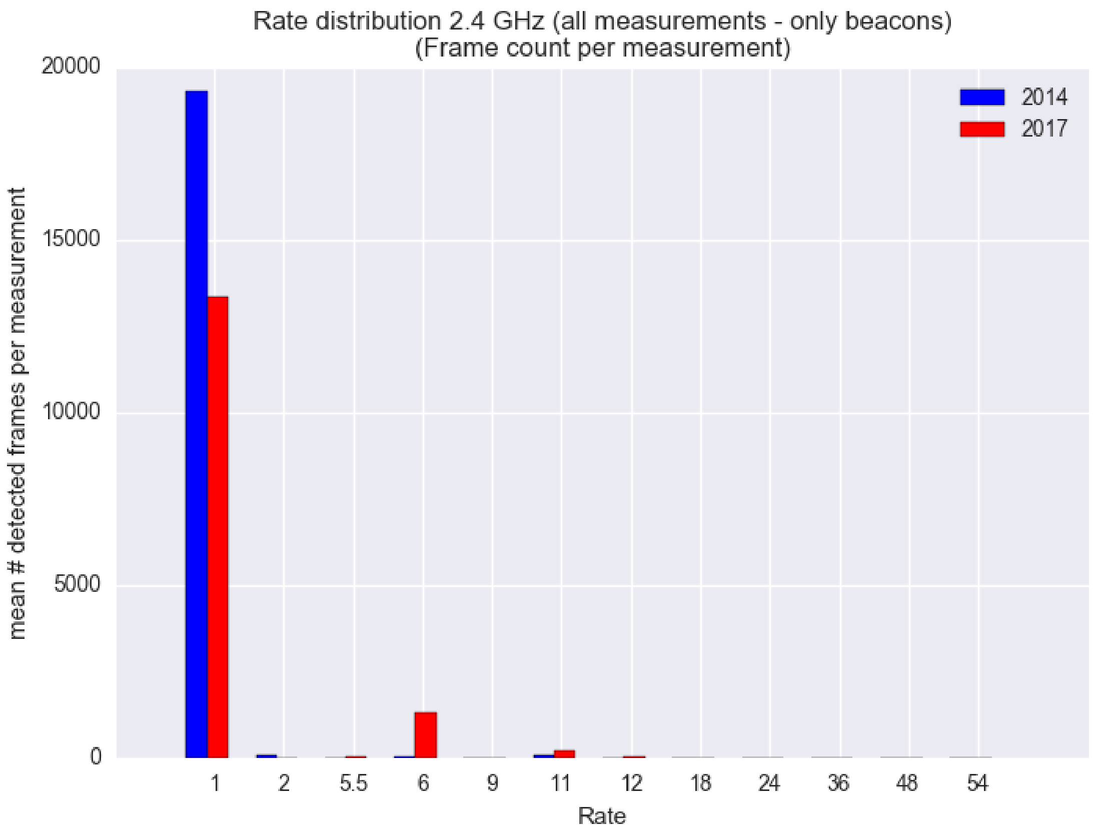


Figure 12 Rate(Mbps) distribution of observed frames at 2.4 GHz

Figure 13 shows the rate distribution for all types of packets. The comparison between 2014 and 2017 shows that significantly more packets are transmitted at higher rates. In particular 1, 6, 12 and 24 Mbps represent a large fraction of all traffic. Again, the measurements show what is observed in the measurement locations, where radio range is inversely related to the rate. What is presented here is what is measured as being visible from the measurement locations. It does not show how frequent each transmit rate is used in all transmissions.

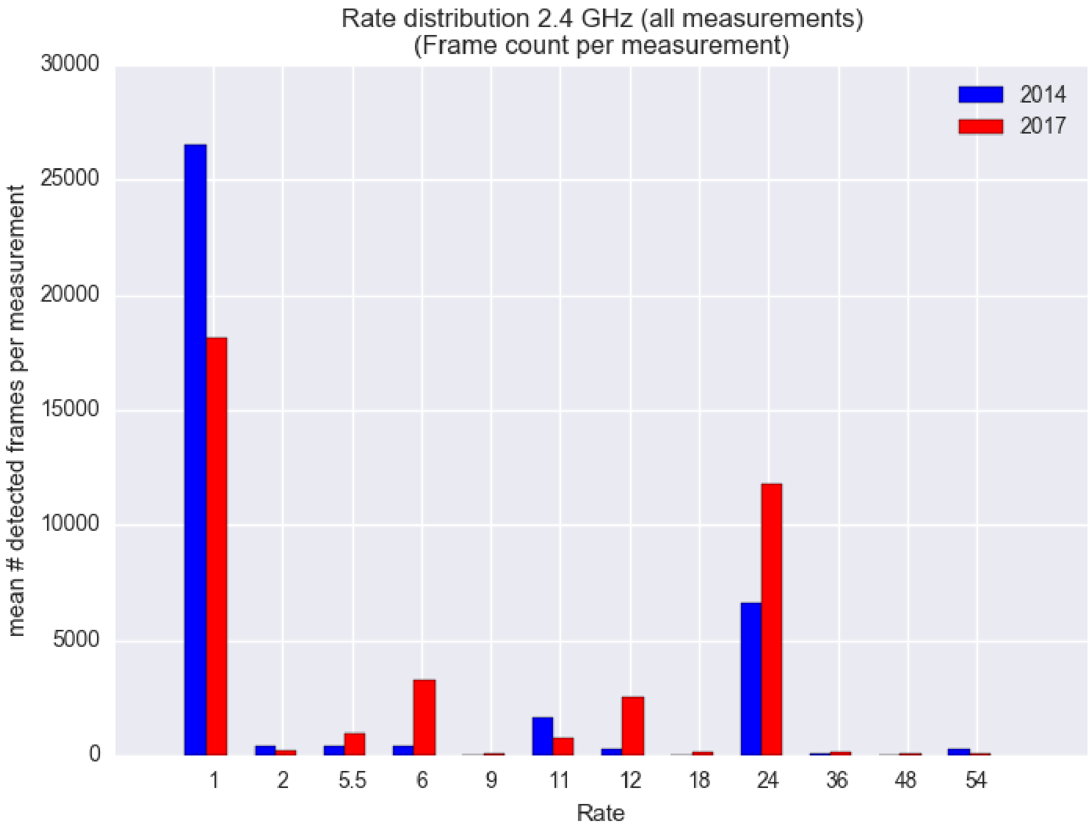


Figure 13 Rate (Mbps) distribution for 2.4 GHz frames

A further analysis of Figure 12 and Figure 13 shows that both in 2014 and in 2017 roughly 75% of all frames at 1 Mbps are beacons. The beacons were hardly present at 6 Mbps in 2014, while representing 60% of all frames detected in 2017.

Overall beacons represented 1/2 of all frames observed in 2014, while 1/3 of all frames in 2017. The average rate of the transmission rate observed increased from 12 Mbps to 14 Mbps. As the range decreases for increasing transmissions rates, the average rate of transmission used by WiFi stations will be higher, and is expected to have increased more.

Figure 14 shows the same traffic, but now expressing the transmissions in airtime. The reduction of 1 Mbps beacons clearly resulted in a reduction of the airtime, but still beacons are dominant in the airtime. Summed for all rates the airtime dropped from 18% to 14%.

The rate distribution measurements suggest that a significant number of APs have disabled (the fallback to) 802.11b, and are configured as 802.11g/n. As a result the occupancy of the spectrum seems to have dropped significantly. The conclusion that transmission has improved through less beacon overhead and a higher throughput is clear.

The amount of traffic measured at 5 GHz is too low for a detailed analysis.

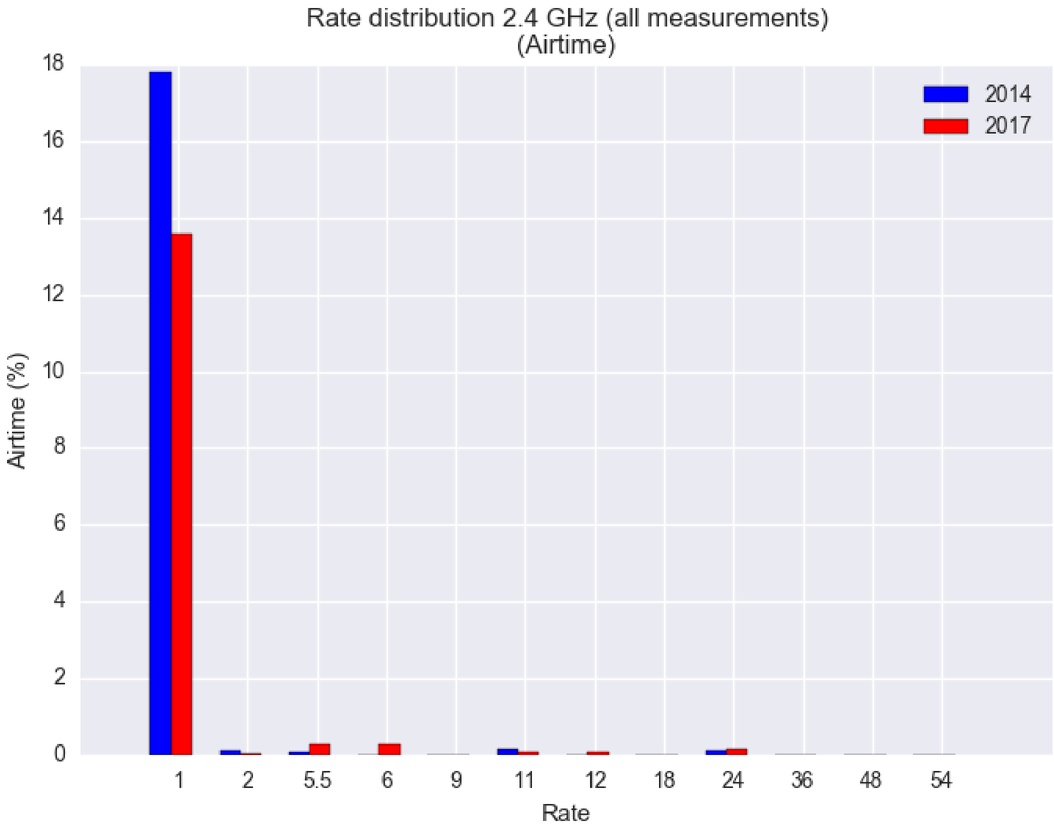


Figure 14 Airtime at 2.4 GHz for physical layer rates (Mbps)

3.5 Mesh

Mesh networking is a network topology with a rich interconnection between the connected devices. In such network multiple routes exist between the devices, where the routes for the wireless traffic is negotiated among the nodes. In a wider definition, the term wireless mesh is also used as a means to identify the wireless extension of a wired infrastructure. The wireless mesh nodes act as repeaters, whereas the network topology is reduced to a tree structure.

A wireless mesh network can be created in multiple ways, some of which are visible from the 802.11 header information (see Paragraph 2.7). Mesh networks can also be based on AP – client communication. In that case, the 802.11 headers are identical to regular headers, and not distinguishable as being mesh by processing the headers.

Table 4 shows the measurement results summed for all measurements. The results show that overall all mesh networking methods are found, but in very low quantities. The percentages are too low to analyse this per environment.

Table 4 Mesh networking measurement results

Method	Fraction of APs
WDS (Wireless Distribution System)	< 1%
IBSS (Independent Basic Service Set)	< 1%
MBSS (Mesh Basic Service Set) – 802.11s	< 1%

The measurements shows that WDS, IBSS and MBSS all do exist, where each represent less than 1% of all stations observed. The very low number of mesh could have some explanations:

- Mesh is hardly used, compared to the vast majority of default modems provided by the operators.
- Typical repeater solutions seem to use AP-client links. So these are indistinguishable from “regular” stations.
- Dual radio mesh systems tend to use 5 GHz for the mesh, which is less visible compared to 2.4 GHz.
- Mesh solutions target larger residents and small offices, which are not the focus areas of the measurements.

For a more conclusive measurement the commercial mesh product offerings could be analysed on identifiable radio characteristics.

3.6 Achievable throughput

The availability of the spectrum is assessed through measuring the achievable throughput in a WiFi connection at a default range, whereas the link is expected to provide a reasonable throughput in a quiet environment. The measured throughput is an indication of how a default WiFi radio is capable of utilizing the spectrum in this environment.

The 2014 measurements are repeated in 2017 on exactly the same locations in 2017, and are extended to some new locations.

The measurements result in a cumulative density function of all throughputs achieved in the measurements. In this section, these results are presented in two ways. This section shows the CDF as measured, and thereafter assesses the quality of the environment in categories that to some extend represent the user experience. The throughput in this analysis is the distribution of throughputs for each individual test of 10 seconds.

In the 2014 measurements, the achievable throughput was also qualified using throughput measurements. In that analysis the average throughput per measurement location was used, i.e. the average over a set of measurements, with the underlying assumption that for a user the performance over a slightly larger interval may be more important than that of a very short time period.

While revisiting the measured data in the current analysis, using the individual 10 seconds measurement results is considered a more appropriate analysis. The 2014 data is therefore re-analysed using the 10 second intervals.

3.6.1. Achievable throughput at 2.4 GHz

Figure 15 compares the measured throughput for all measurements of 2014 that are repeated in 2017. The figure shows the cumulative probability of 10 second measurement intervals. The figure shows that the achievable throughput has become better. More measurements show a higher throughput. The probability of having a very bad link has increased slightly, but the probability of achieving a very good link has increased considerably.

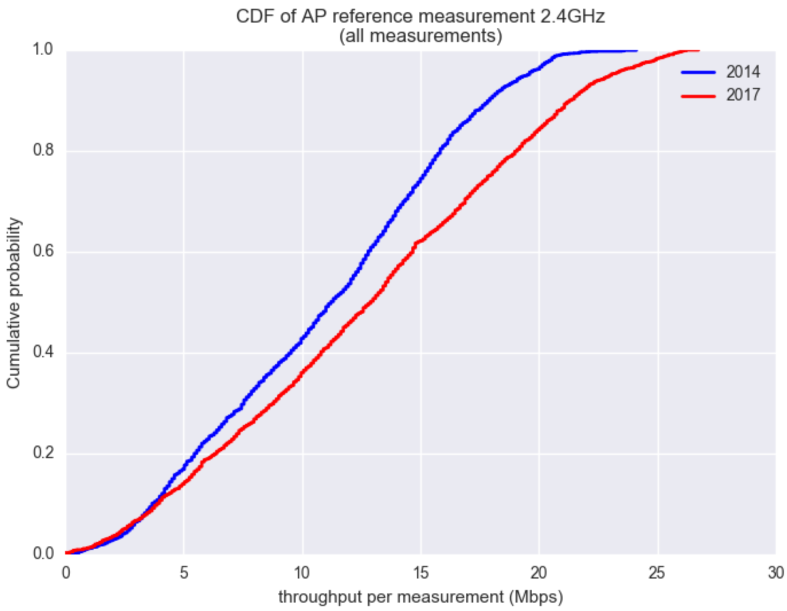


Figure 15 Cumulative distribution of throughput measurements at 2.4 GHz

Figure 16 shows the quality assessment. The figure confirms that the number of environments that can be qualified as being "very good" has increased. The environments qualified as "bad" or "very bad" have not changed significantly in these measurements. The figures below split the results per environment type.

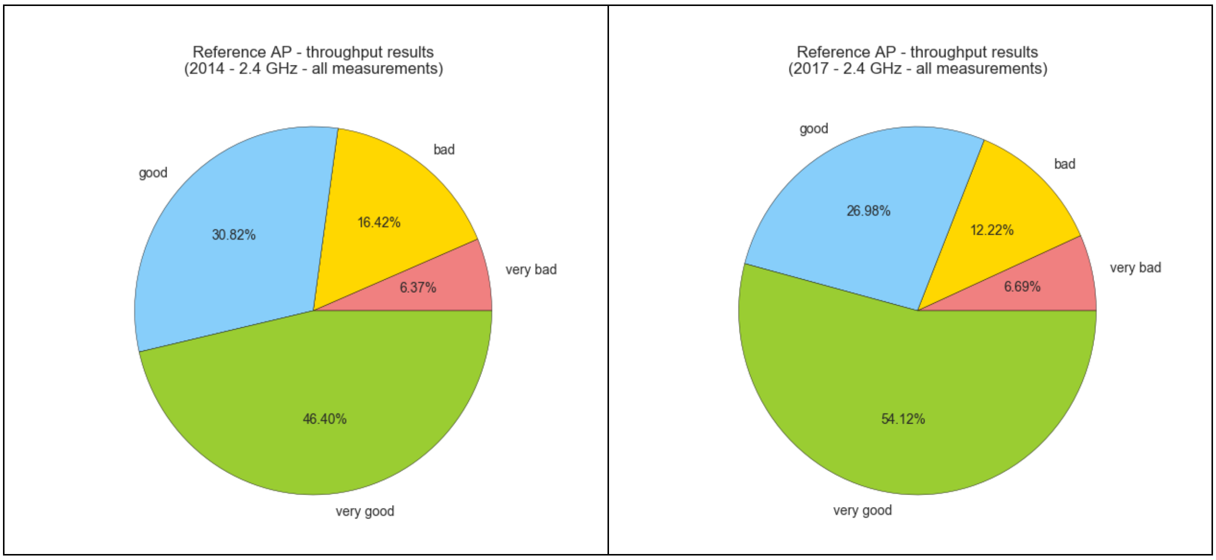


Figure 16 Quality assessment for all environments at 2.4 GHz

Figure 17 shows that the performance in the business park environment has mainly increased significantly. In this environment the measurements show also some deterioration for low performance situations, and a strong improvement for high performance situations. This is not reflected in a significant increase in the fraction of measurements that are assessed at “very good”, as the limit between good and very good was set at 12 Mbps, whereas the large improvement was measured at higher rates. Also some limited increase is found for bad links.

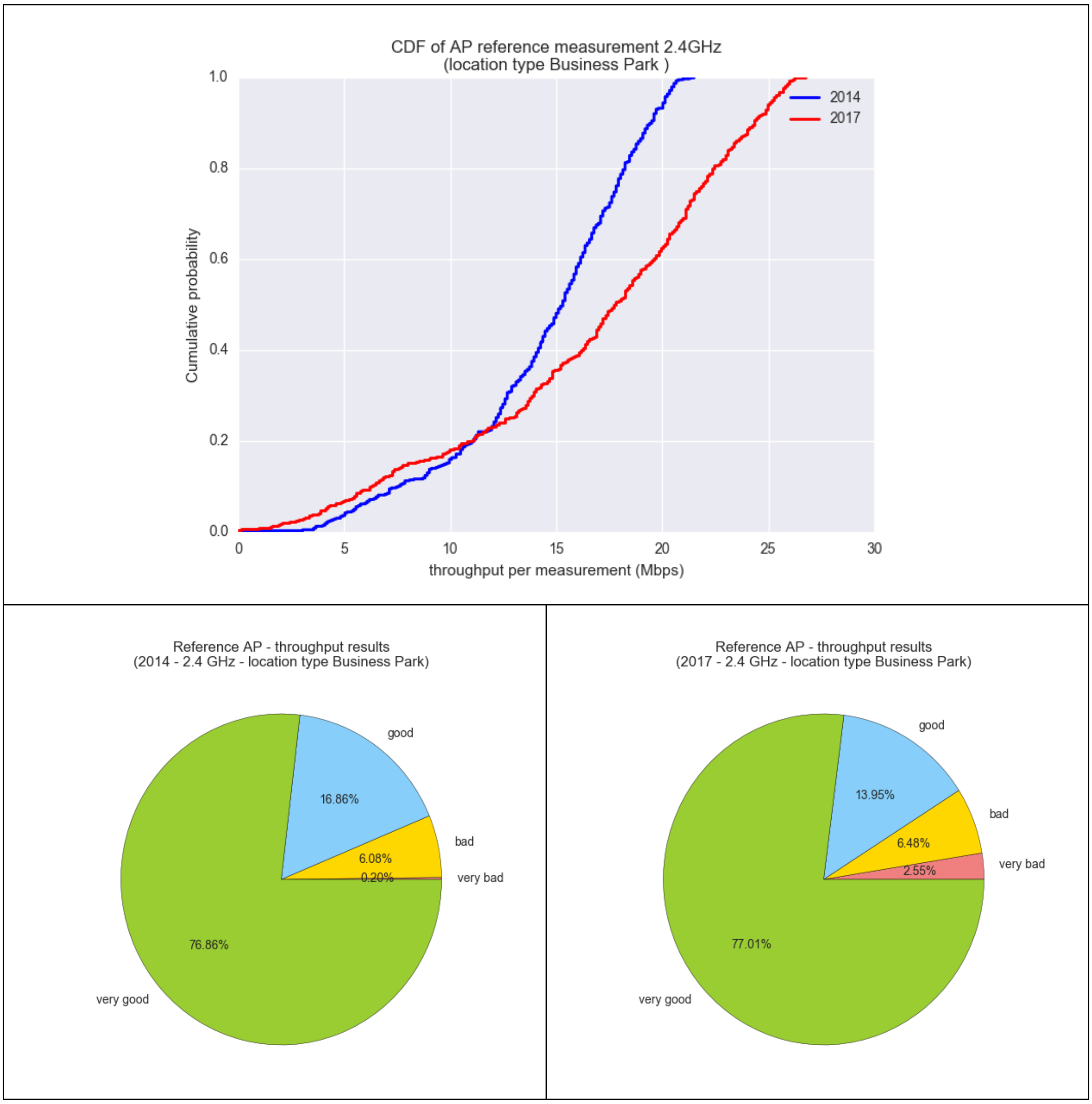


Figure 17 Performance assessment for business park at 2.4 GHz

Figure 18 shows the performance assessment for the city centre environment. The city centre environment appears to have become more extreme, and somewhat worse. The probabilities of a very bad link and of a very good have increased clearly. The probability of having either a good or very good link decreased for over 70% to around 60%. Overall the performance was moderate in the city centre.

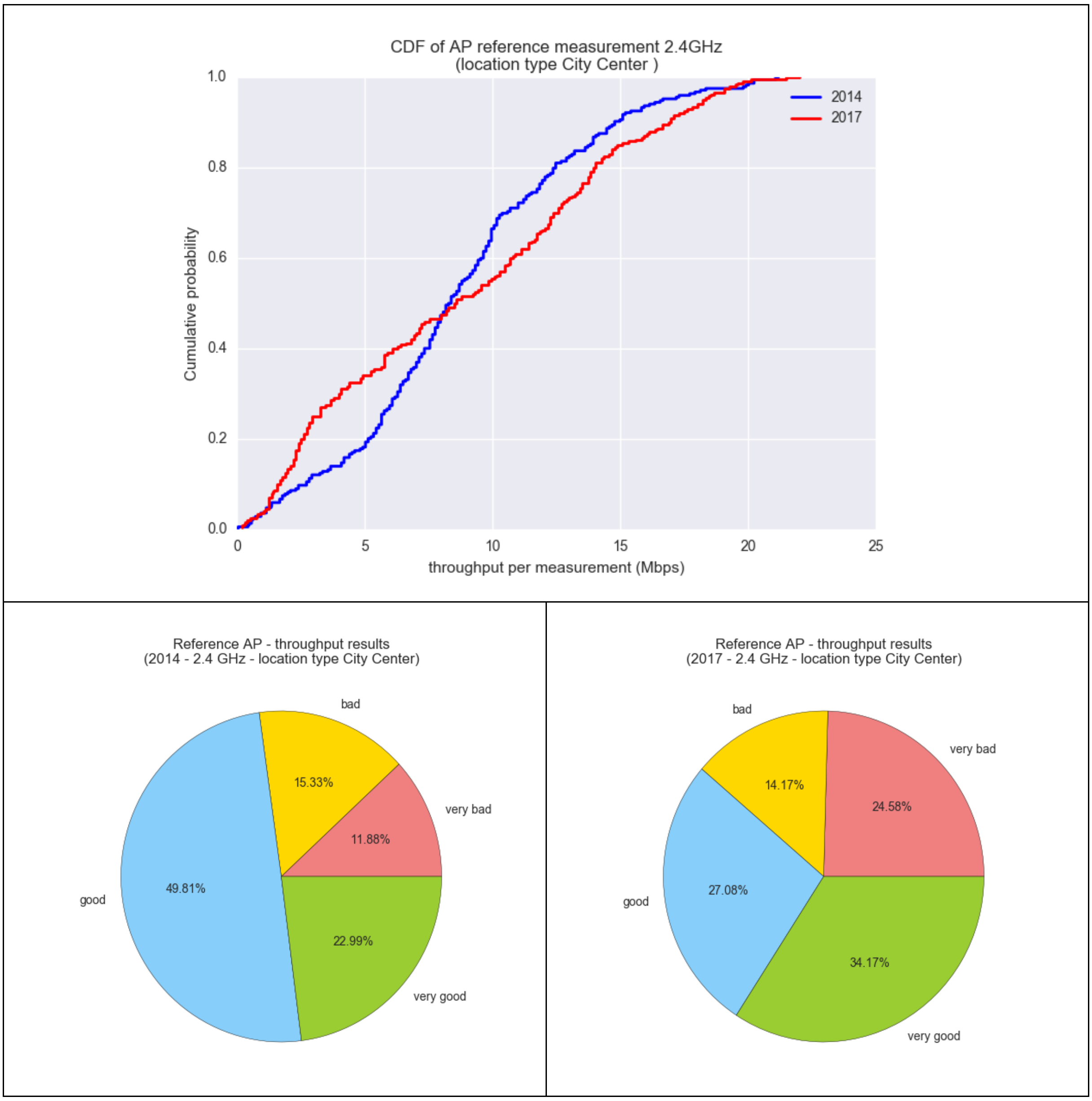


Figure 18 Performance assessment for city centre at 2.4 GHz

Figure 19 shows the performance assessment for the residential high rise environment. The CDF shows that the probability of having a very low throughput as well as a very high throughput have decreased. The impact on the assessed quality suggests a more extreme change. This is however primarily due to applying stringent limits for the qualification, where a number of links are on the edge of being "bad" or "very bad". Still the reduced number of "very bad" environments is clear and good to notice.

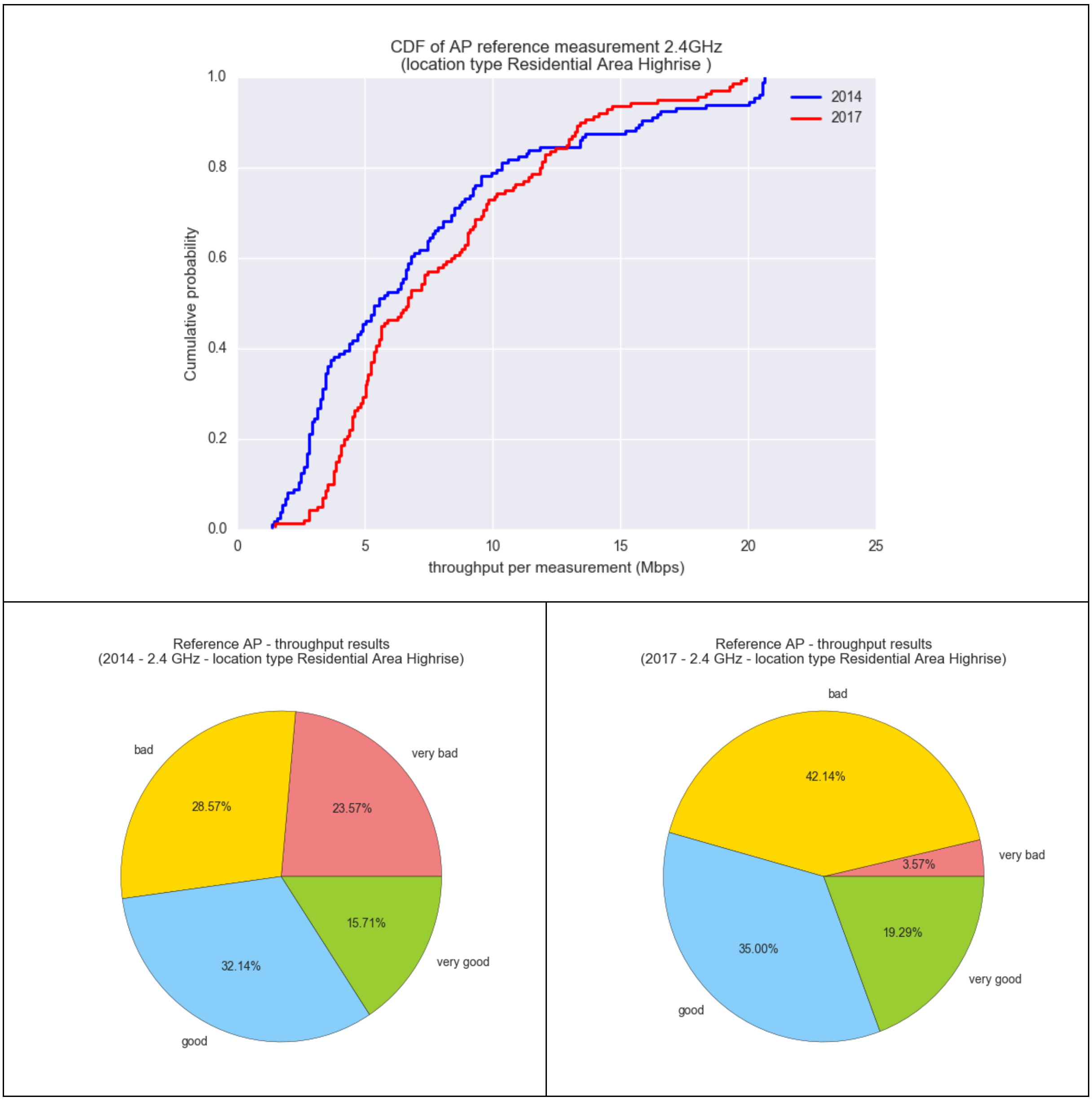


Figure 19 Performance assessment for residential high rise at 2.4 GHz

Figure 20 shows the performance assessment for the residential low rise environments. The change in measured performance is a larger probability of having a high throughput under all conditions. The increased probability of having a higher throughput is also reflected in the quality assessment, where the probability of having a “good” or “very good” link increased significantly.

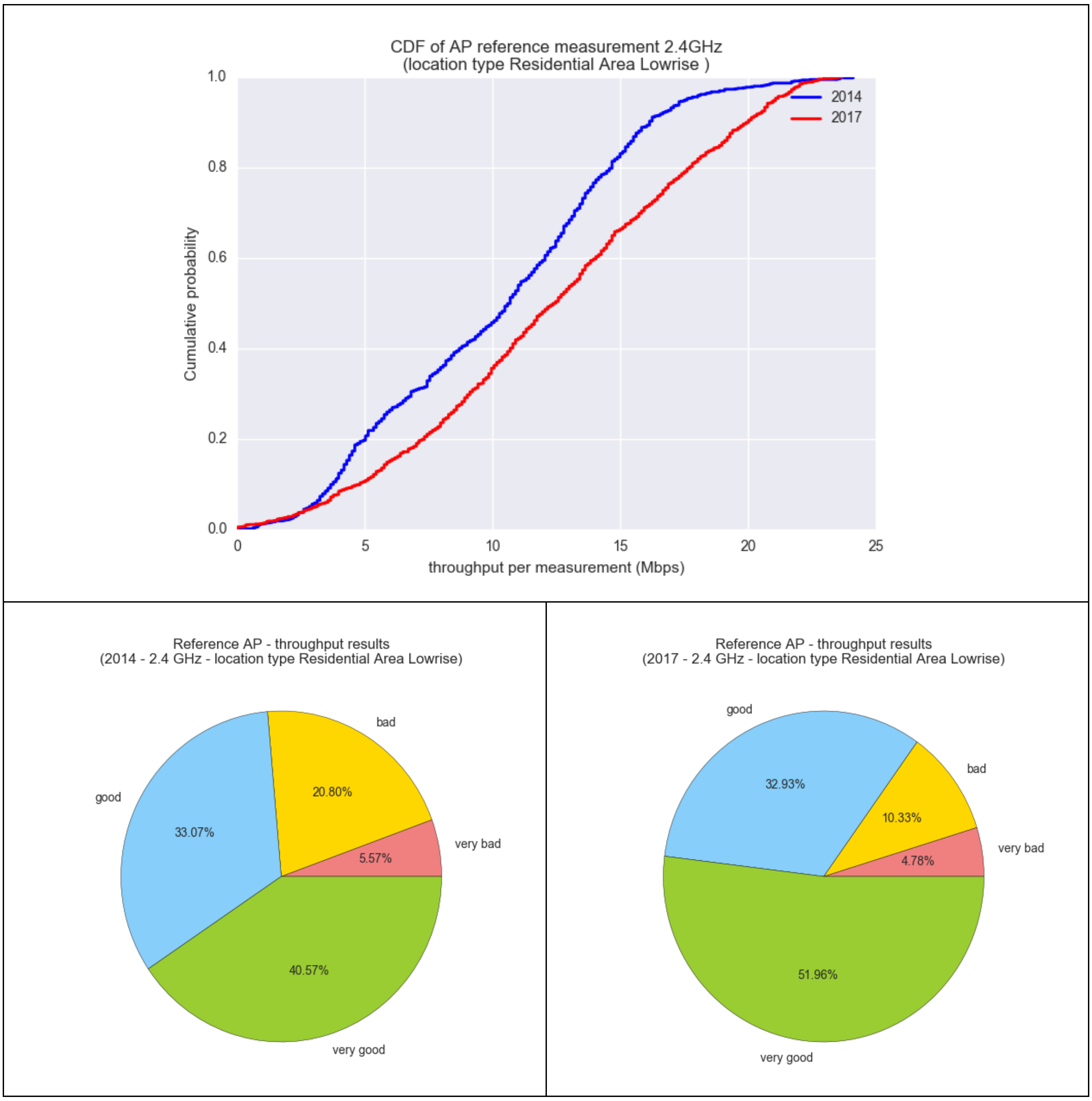


Figure 20 Performance assessment for residential low rise at 2.4 GHz

3.6.1. *Achievable throughput at 5 GHz*

Figure 21 shows the quality assessment for all locations at 5 GHz. The measurement result shows an improvement of the assessed quality, whereas the quality was already extremely good in the 2014 measurements. The measurements are executed on channel 44. Section 3.3 showed that the number of APs configured on channel 44 has decreased between 2014 and 2017. The improved quality may be due to the reduced number of APs on this channel. Overall the performance at 5 GHz was very good and is still very good, which is due to the fact that 5 GHz provides abundant room for WiFi transmissions.

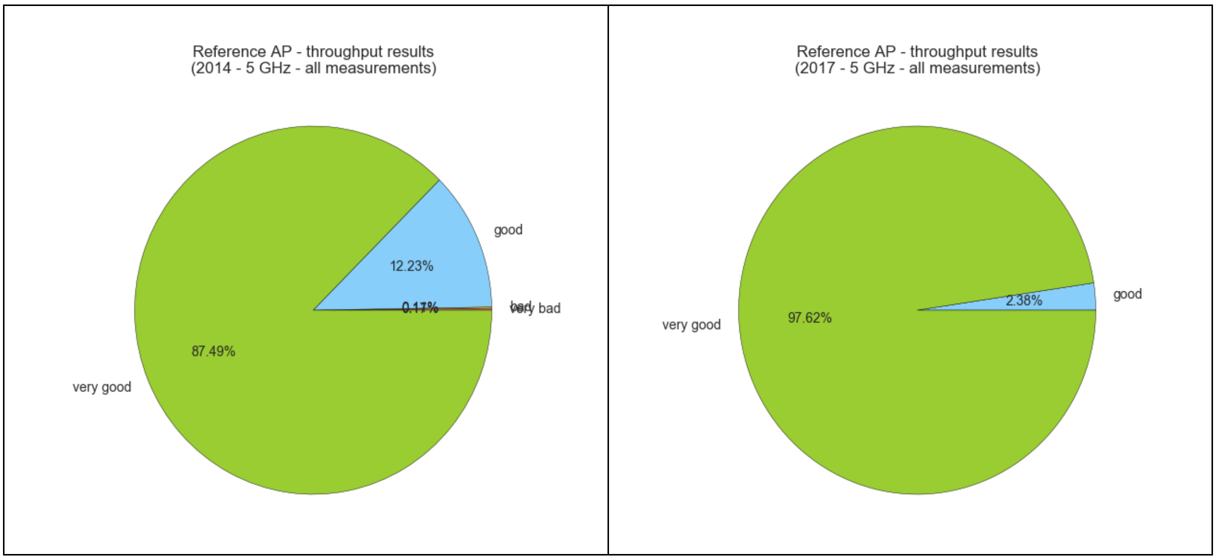


Figure 21 Performance assessment for all locations at 5 GHz

Figure 22 shows the results for the business park environment. The performance in this environment is completely in line with an overall performance at 5 GHz.

Figure 22 Performance assessment for business park at 5 GHz

Figure 23 shows the 5 GHz performance for the city centre environment. In contradiction to the other environments, the performance in the city centre has reduced compared to 2014. The performance is still very good, but it has declined. The amount of WiFi present at 5 GHz in the city centre is also higher than for the other environments.

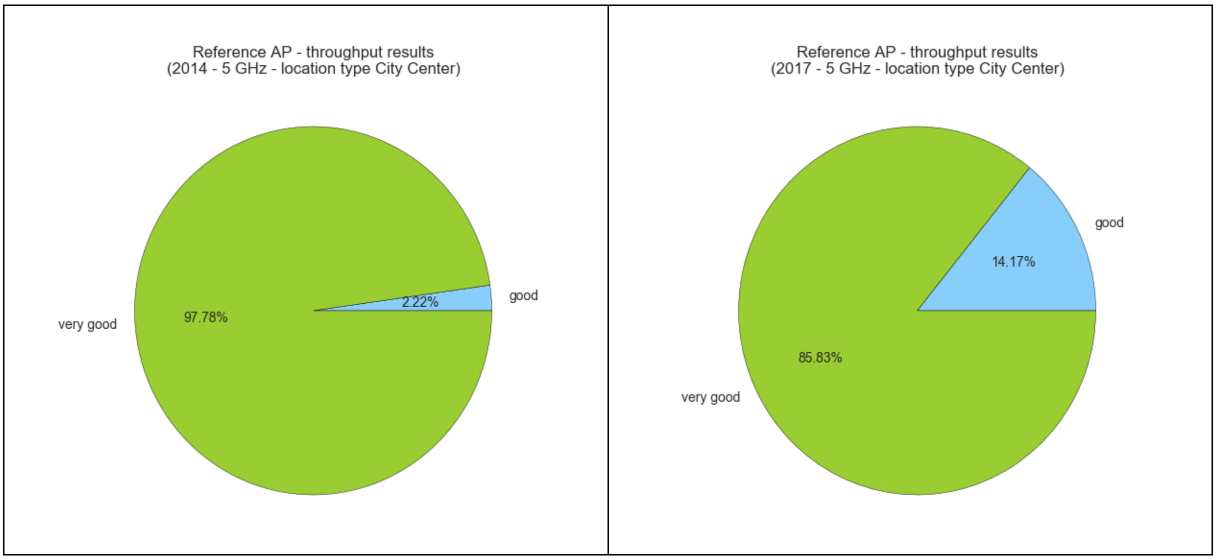


Figure 23 Performance assessment for city centre at 5 GHz

Figure 24 shows the results for the residential high rise environment. The bad and very bad conditions in 2014 might be considered outliners, as the percentages are very low. The performance on 5 GHz in this environment was extremely good.

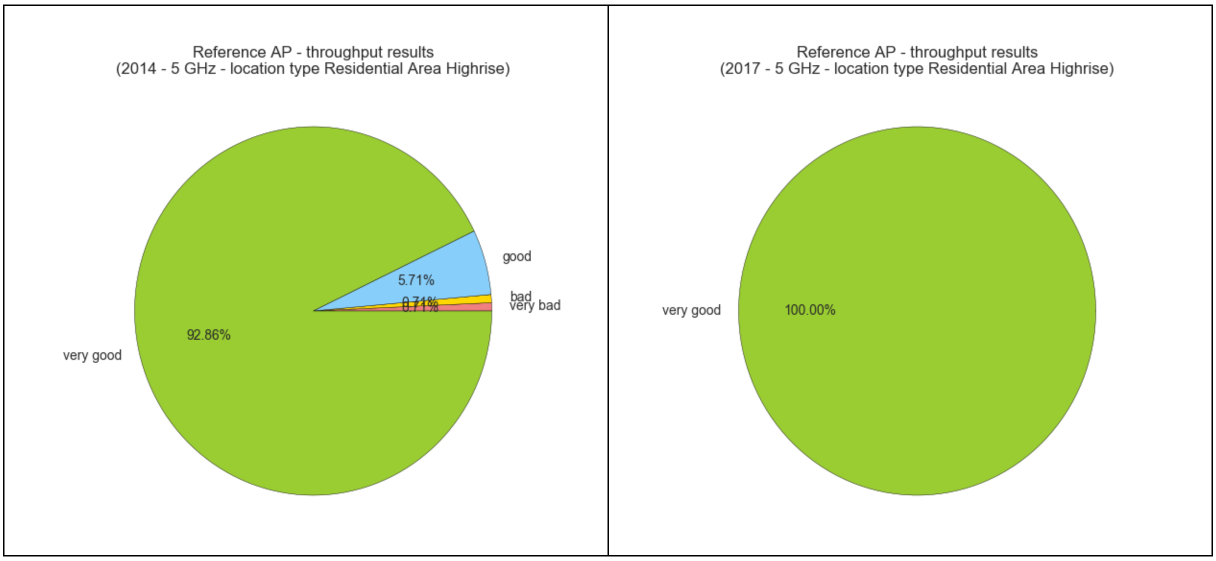


Figure 24 Performance assessment for high rise at 5 GHz

Figure 25 shows the performance at 5 GHz in the residential low-rise environment. The performance in this environment is in line with that of the other environments.

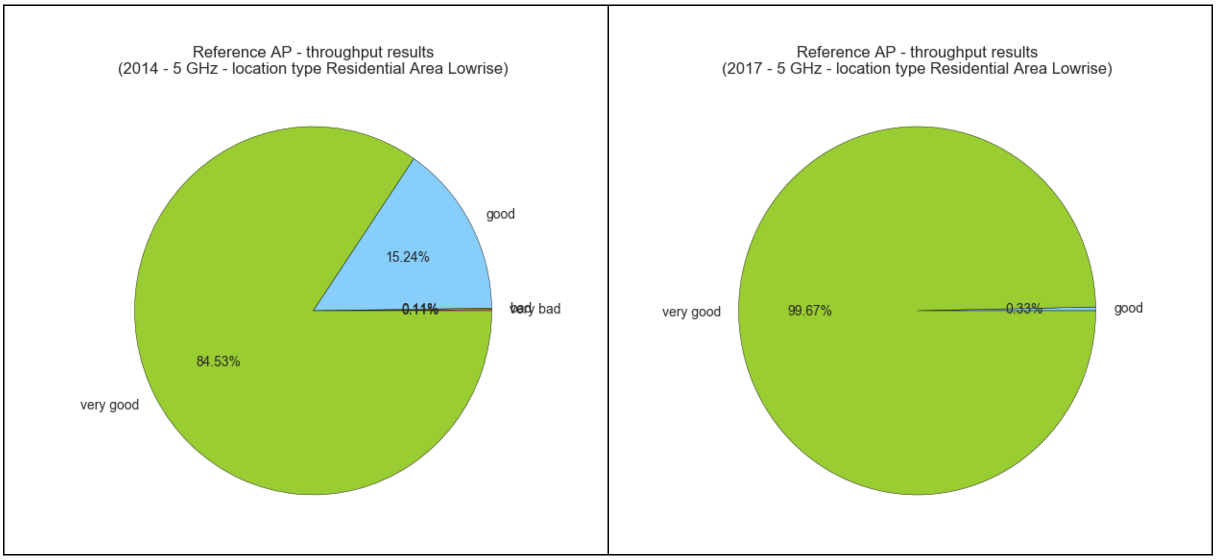


Figure 25 Performance assessment for low rise at 5 GHz

Overall the 5 GHz frequency band provides abundant room for WiFi communications. The trend towards more use of the 5 GHz band has so far not resulted in considerable deterioration in the observed performance.

3.8 Vendors

In order to be able to communicate WiFi devices in a single WiFi network need to have unique MAC addresses. The addressing can be either universal or local. Universal addresses are uniquely assigned to each device by the manufacturer. The first three octets identify the manufacturer and are known as the Organizationally Unique Identifier (OUI). Local addresses can be random, and are therefore useless within the scope of this investigation.

The measurements log the MAC addresses of all APs, and group these results per manufacturer. Table 5 shows the top-25 of manufacturers in the measurements sorted per environment. For all environments "local" is dominantly present. "Local" represents the case where the "local-bit" is turned on, which indicates that the MAC address is generated locally. Such a MAC address has no relation to the manufacturer. This setting can be used for various purposes, which makes this information not useful for identifying the manufacturer. Further, it should be noted that the sample from the measurements is limited, so the percentages should be considered with care.

The results show a clear dominance of Cisco Systems in the business park environment. From the top 5, Cisco and HP are the more typical high-end manufacturers, whereas ZTE, TP-Link, Senao and Cisco-Linksys are normally considered consumer grade equipment.

The city centre shows a dominant for Ruckus Wireless, which is a typical high-end solution. Considering the top 5, also Xirrus and Cisco Systems are typical professional solutions. ZTE and Arcadyan are manufacturers that are frequently present in the modems provided by the ISPs, so their dominant position is likely due to the presence of the ISPs (Ziggo, KPN, etc.). This is similar to the residential areas.

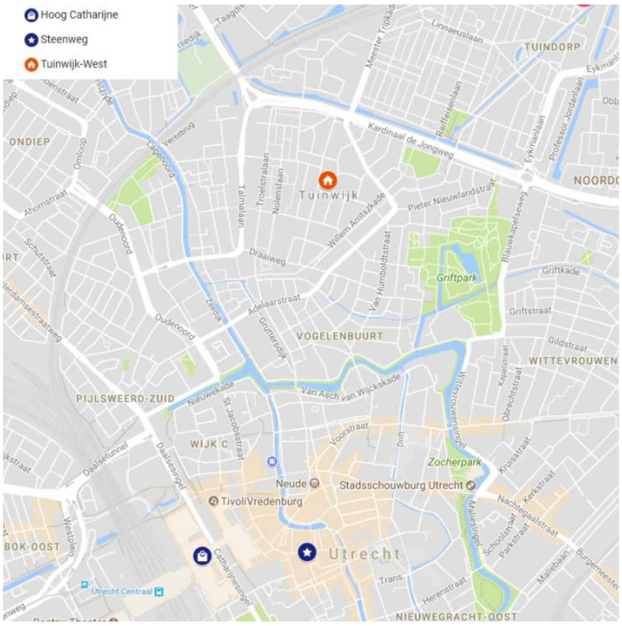
In both high rise and low rise residential environments Compal, Arcadyan, ZTE and Samsung are dominant. The dominant position of these manufacturers is linked directly to the standard modems provided by the ISPs (Arcadyan – KPN, Compal – Ziggo, Samsung – Ziggo/UPC, Pegatron – Ziggo/UPC, ZTE – KPN, Technicolor – Ziggo). TP-Link is a consumer brand currently not linked to the ISP modems.

Table 5 Manufacturers of APs

Business Park		City centre		High rise		Low rise	
local	14.9%	local	21.5%	Local	15.6%	Local	18.2%
Cisco Systems	14.5%	Ruckus Wireless	20.0%	TP-Link	11.6%	ZTE	17.0%
HP	8.4%	ZTE	6.7%	Compal	11.4%	Arcadyan	10.8%
ZTE	6.8%	Arcadyan	4.3%	Arcadyan	11.2%	Compal	7.1%
TP-Link	4.8%	Xirrus	4.0%	Samsung	9.3%	Samsung	5.5%
Senao	4.2%	Cisco Systems	3.9%	ZTE	8.6%	Sitecom	5.2%
Cisco-Linksys	4.1%	Aruba Networks	3.8%	Technicolor	3.0%	TP-Link	4.2%
DrayTek	3.7%	Samsung	3.2%	ASUS	2.9%	Zyxel	3.0%
Netgear	3.4%	Compal	3.0%	DrayTek	2.7%	AVM	3.0%
Arcadyan	3.2%	HP	2.4%	Pegatron	2.1%	Pegatron	2.9%
Aerohive	3.1%	Extreme Networks	2.0%	Hon Hai	1.9%	Huawei	2.8%
Aruba Networks	3.1%	Aerohive	1.8%	Cisco-Linksys	1.9%	Technicolor	2.5%
Zyxel	2.3%	TP-Link	1.7%	Netgear	1.9%	Netgear	2.4%
ASUS	2.0%	DrayTek	1.6%	Hewlett Packard	1.7%	ASUS	1.7%
Fortinet	1.7%	AVM	1.4%	Apple	1.7%	DrayTek	1.6%
AVM	1.6%	Ubiquiti	1.3%	Senao	1.5%	Cisco-Linksys	1.3%
Ubiquiti	1.5%	Hewlett Packard	1.3%	AVM	1.5%	Apple	1.3%
Sitecom	1.4%	Juniper Networks	1.2%	Ruckus Wireless	1.3%	Technicolor	1.2%
Apple	1.3%	ASUS	1.1%	Askey	1.1%	Hon Hai	1.2%
Compal	1.3%	Senao	1.1%	Sitecom	1.1%	Hewlett Packard	1.1%
Sophos	1.2%	Apple	1.0%	Comtrend	1.0%	Askey	1.0%
Ruckus Wireless	1.0%	Technicolor	1.0%	Cisco Systems	0.8%	Comtrend	0.6%
Thomson	0.9%	Sitecom	0.9%	Ubiquiti	0.6%	Aerohive	0.5%
4IPNET	0.9%	Huawei	0.9%	EFM	0.6%	Hi-flying	0.5%
Hon Hai	0.7%	Netgear	0.8%	Thomson	0.4%	Belkin	0.3%

3.9 Additional urban measurements

The 2017 measurement campaign has been extended with measurements in the urban area of Utrecht. For the trend analysis of 2017 vs 2014, these measurements are excluded. This section compares the performance in the additional area to the other areas for 2017.



Utrecht:

Location 35.1b: Hoog Catharijne

Location 36.1a: Steenweg

Location 37.4a: Tuinwijk-West

Figure 26 Additional measurement locations in the 2017 measurement campaign

This comparison needs to be considered with care. The number of measurements per location is limited. The general approach in the research is to create statistics by combining measurements from various locations that have similar characteristics. This section only deals with the additional measurements. A direct result of this focus is that the statistical accuracy is limited for this comparison, due to a small number of samples.

Figure 27 explores the performance of Hoog Catharijne versus other shopping malls. The figure compares Hoog Catharijne (location 35) to Zuidplein Rotterdam (location 23), de Klanderij Enschede (location 2) and the average over all shopping malls. The result clearly shows that Hoog Catharijne and Zuidplein are comparable, whereas de Klanderij is not. This resemblance may be due to the fact that both combine shopping and a train station, whereas the latter one is only a shopping mall. So, the presence of the train station may be dominant for the performance in 2.4 GHz.

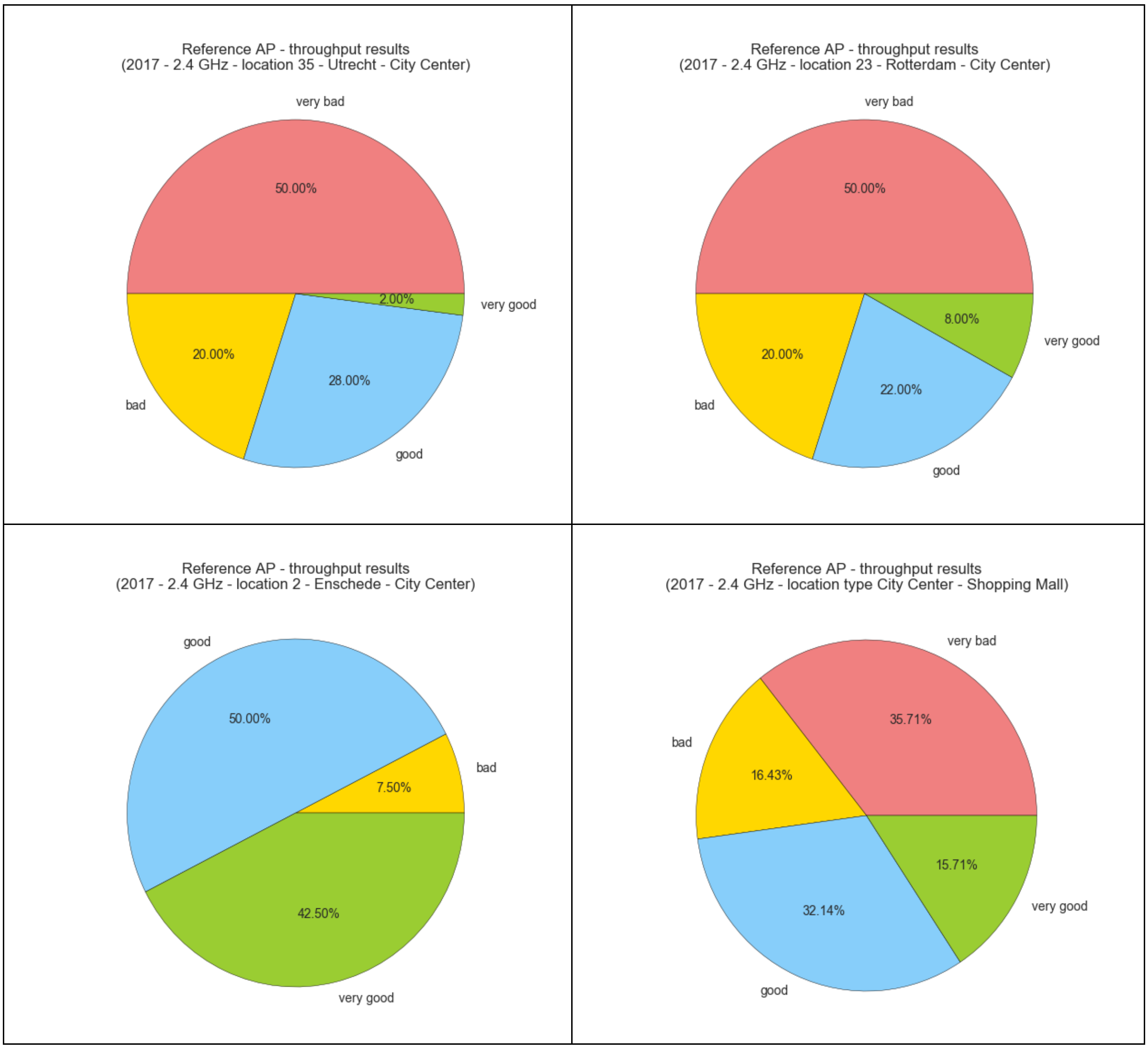


Figure 27 Performance assessment for Hoog Catharijne versus other shopping malls at 2.4 GHz

Figure 28 explores the performance in the Steenweg versus other shopping areas. The figure compares Steenweg (location 36) to the average of all other shopping areas visited during the measurements.

The comparison shows that the probability of having a "very good" or "good" performance was equal. The probability of a "very good" or "very bad" link was however much smaller than for the average over all locations. So, the performance in the Steenweg was less extreme.

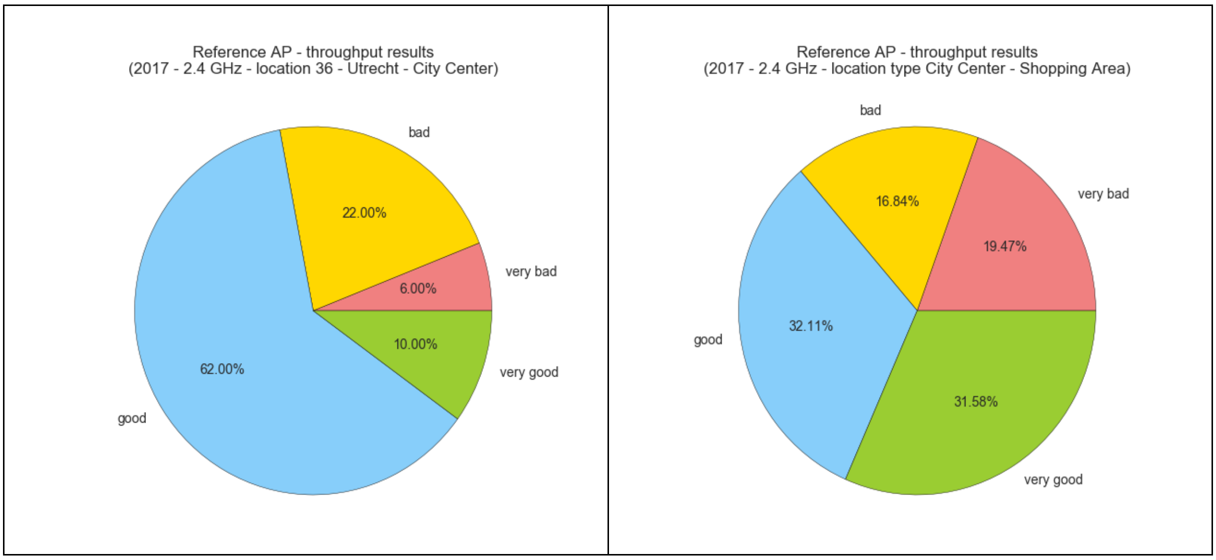


Figure 28 Performance assessment for Steenweg versus other shopping areas at 2.4 GHz

Figure 29 explores the performance in Tuinwijk-West versus other residential low rise areas with houses in a row. The figure shows a much worse performance than for the average over these locations, which is likely due the low number of samples in the individual measurement, and is likely not due to the particular environment.

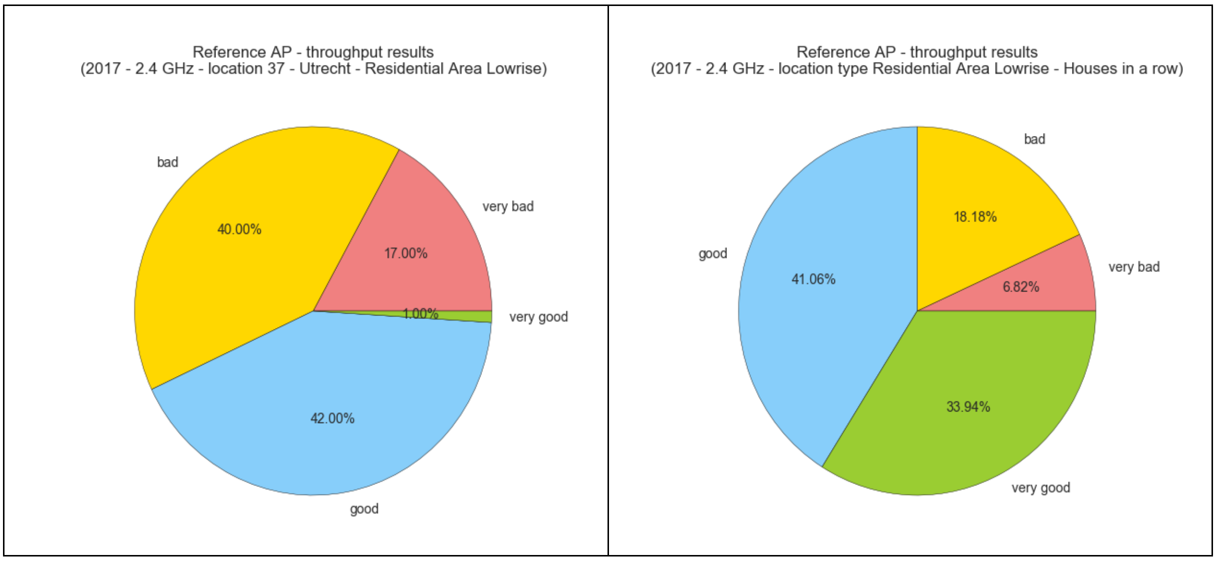


Figure 29 Performance assessment for Tuinwijk-West versus other residential low rise – houses in a row areas at 2.4 GHz

3.10 Spectrum usages in 2.4 GHz and 5 GHz

Spectrum utilization is logged per location for the 2.4 and 5 GHz using the (low end) WiSpy tool. The WiSpy tool is a lightweight tool, providing a superfluous image of the presence of radio signals in the observed spectrum. This tool is not suitable for an in-depth analysis of radio signals.

These spectrum measurements are executed directly before the throughput measurements. Comparing the spectrum measurements to the performance measurements shows a correlation. The performance measurements are executed on channel 11 using 'iPerf' as a tool. Figure 30 shows a scatter plot of the measured channel utilization versus the measured throughput. The figure shows that some correlation exists.

The figure shows that high channel utilization does limits the achievable throughput, but that on the other hand, a low channel utilization does not guarantee a high achievable throughput. This result suggests that WiFi is vulnerable to smaller interference sources.

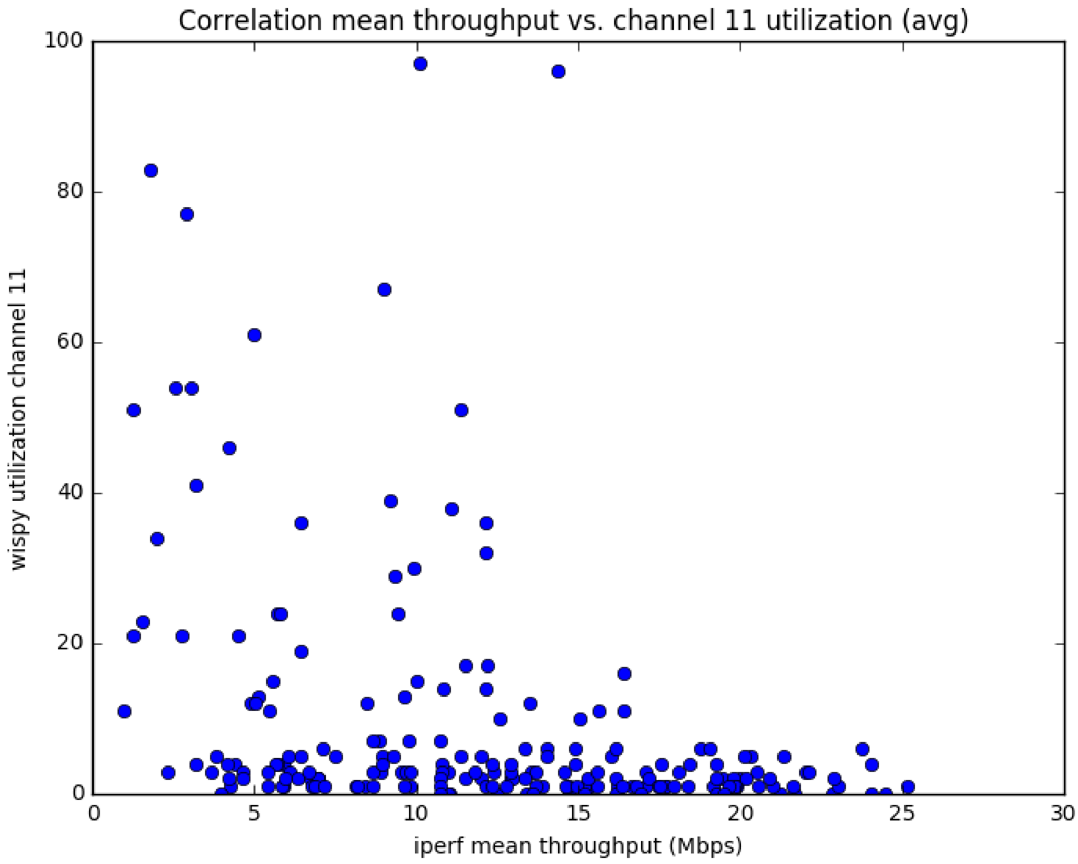


Figure 30 Correlation between mean throughput and channel utilization

When analysing individual spectrum graphs, the 2.4 GHz spectrum is clearly used for a diverse set of applications. This is best seen from a number of examples. The figures are waterfall plots, where the signal strength in dBm is plotted versus the frequency over time.

Figure 31 shows an example spectrum measurement in a busy city centre environment. The plot shows quite clearly three active WiFi carriers on channels 1, 6 and 11. In this case little other sources seem to be present. Figure 32 shows another example, where the environment is much more crowded. The same main WiFi carriers are visible, but the amount of noise in the background suggests the presence of non WiFi signals.

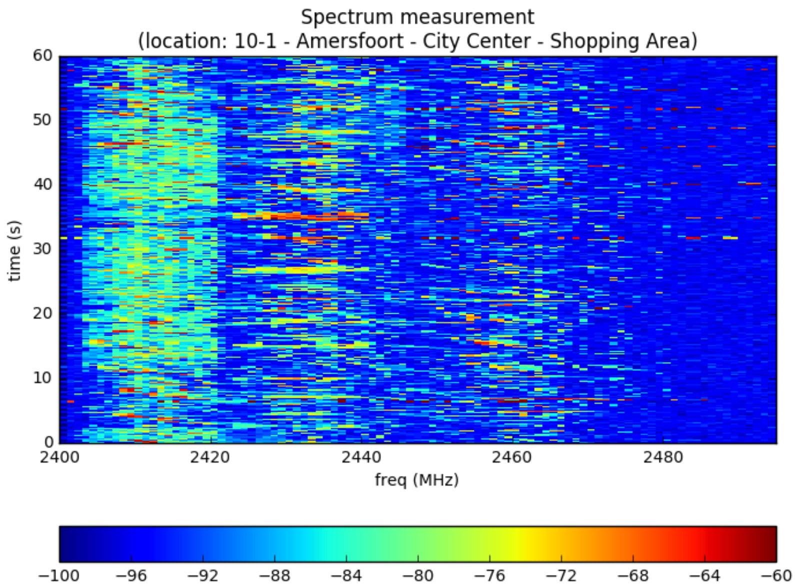


Figure 31 Multiple WiFi carriers in a busy environment (measurement in dBm)

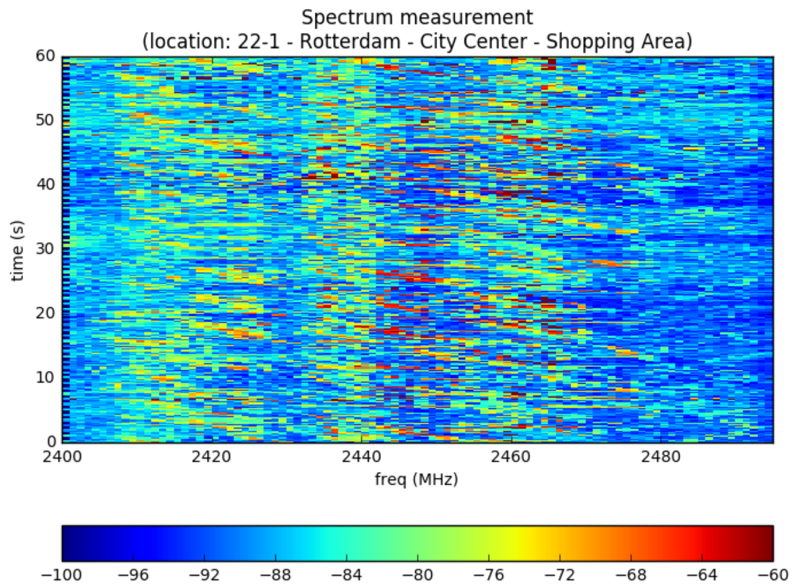


Figure 32 Multiple WiFi carriers in a busy environment (measurement in dBm)

Figure 33 shows an example that is seen multiple times. A strong signal seems to be present that has its centre frequency below 2.4 GHz. It looks as if a signal spills over into the 2.4 GHz band. Figure 34 suggests the same, though due to the presence of WiFi signals it is harder to validate.

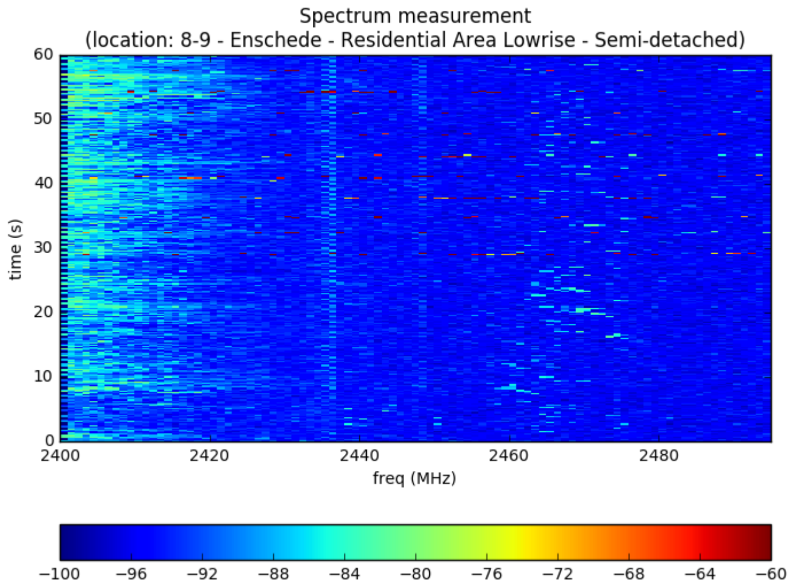


Figure 33 Signal at the edge of the spectrum (in dBm)

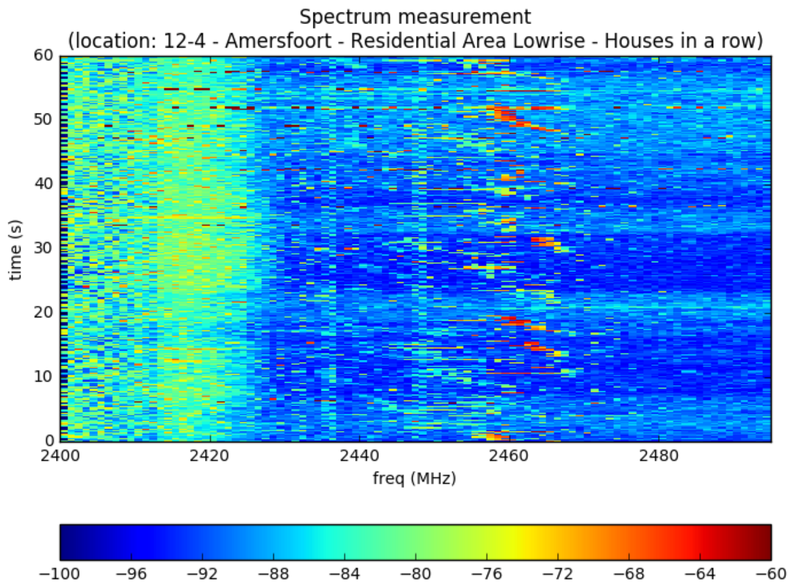
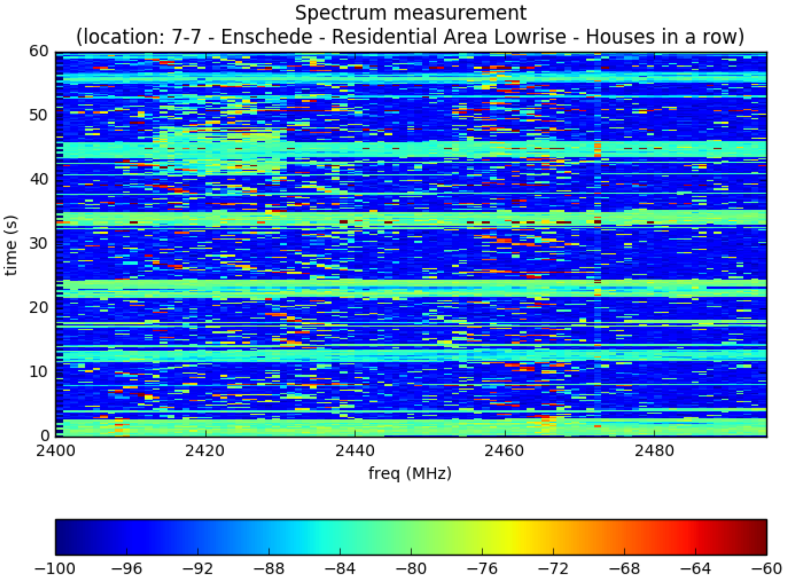
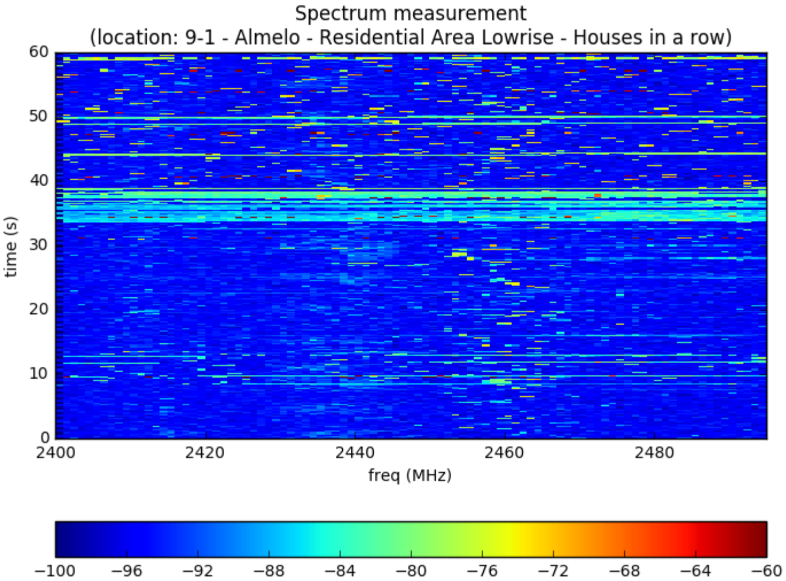


Figure 34 possible signal at the edge of the spectrum (in dBm)

Figure 35 shows three examples of what was seen multiple times. An intermittent signal is present that transmits a signal wider than the 2.4 GHz band. When returning to the same locations at a different moment, the measurement showed that this signal is not always present.





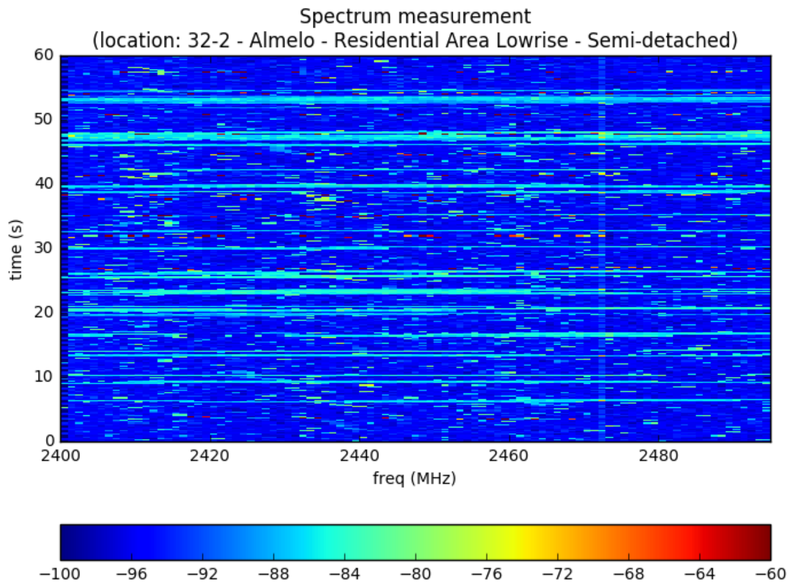


Figure 35 Intermittent signal, wider than frequency band (in dBm)

Figure 36 shows an example of a narrowband signal that is continuously present. Comparing 2014 and 2017 shows that the same signal seems to be present at exactly the same frequency at the same location. Typically such a narrowband signal is measured at different measurement points in the same neighbourhood, triangulation is possible.

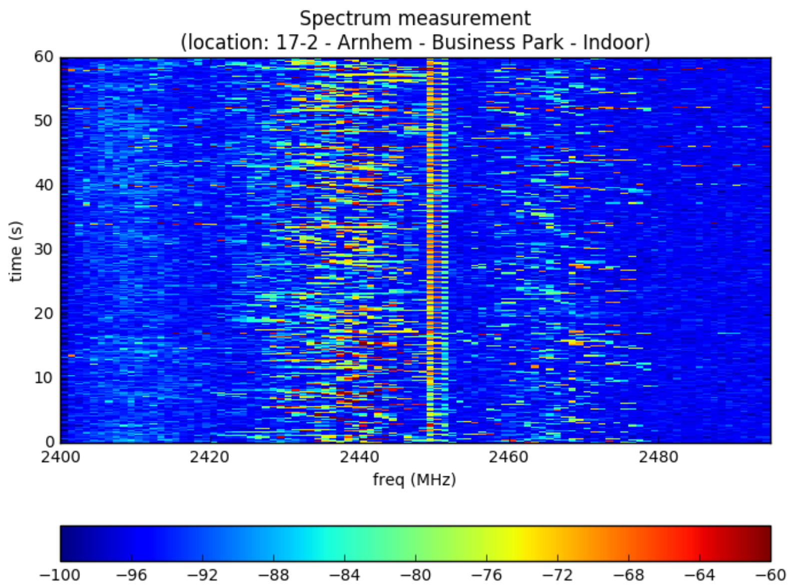


Figure 36 Continuous narrowband signal (in dBm)

Figure 37 shows two examples of a busy 5 GHz environment. The examples show that the 5 GHz band is still nearly empty.

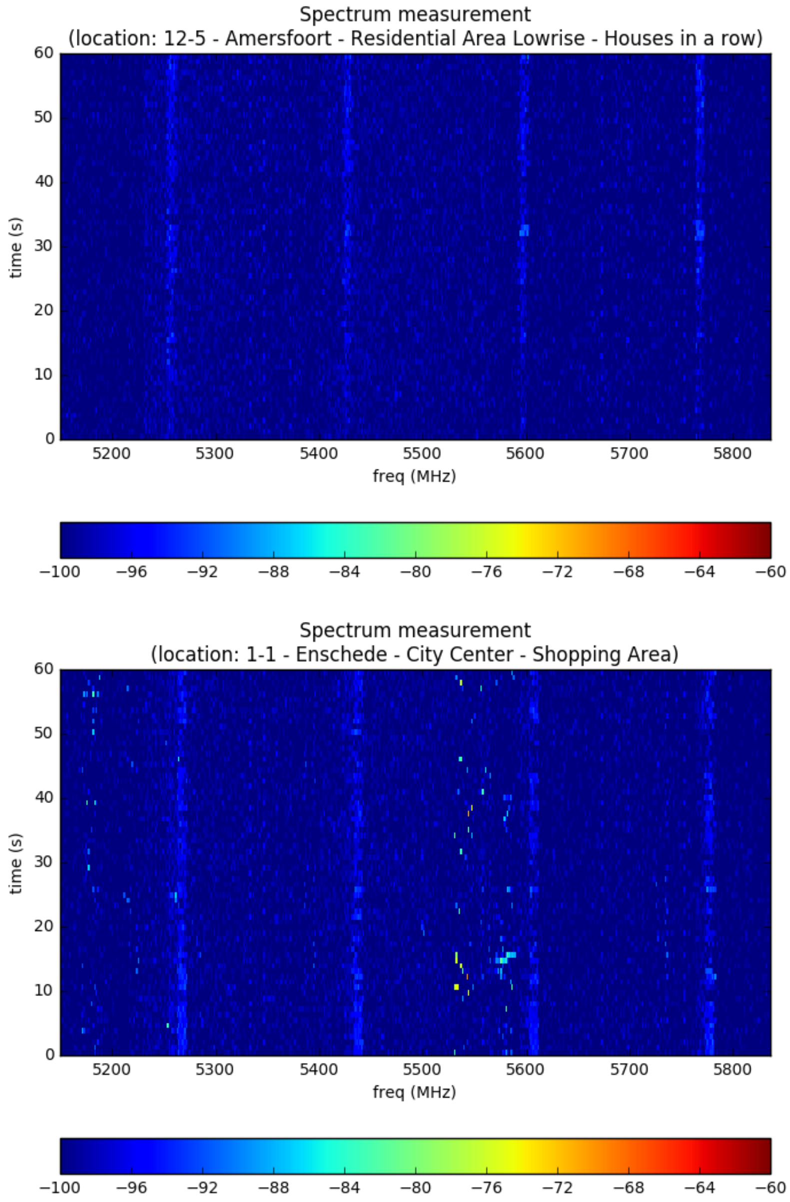


Figure 37 Busy 5 GHz environment (in dBm)

3.11 The effect of information campaigns

Since the measurement project of 2014, various developments have taken place that all influence the use of WiFi, resulting in the performance observed in this measurement campaign.

Most WiFi equipment has a relative short lifespan of around three years. This is due to a number of factors:

- The technology is cheap.
- WiFi is used much in operator bound equipment, where contracts have a significant churn.
- Also the technology is still evolving rapidly.

A large part of the equipment that is measured in the current campaign is the replacement of equipment that was active in the previous campaign. The measured difference may be due to evolving equipment, including different default settings. The fact that much equipment is operator bound also relates to the effect of default settings by operators, as many consumers do not change default settings as long as these provide reasonable performance.

Operators take increasingly responsibility for the performance of WiFi. As part of this responsibility, operators were running information campaigns already in 2014 to empower the end-users for optimizing their WiFi performance. More recently operators focus more on providing a support engineer when installing WiFi, who is trained in optimizing the WiFi performance in the consumers household.

Also Agentschap Telecom (AT) has added to the empowerment of end-users by providing recommendations for optimizing WiFi in case of under performance of the connection. Similar recommendations can be found on the websites of ISPs.

Assessing the effect of information campaigns through analysis of the measurements is to be done with great care, as its effect cannot be distinguished from the effects of replacement of equipment and technology or optimizations by operators.

When considering the individual recommendations of AT, the following is observed:

In case of interference, change the AP channel

Section 3.3 described the AP channel distribution. The distribution of channel 1, 6 and 11 was more or less even in 2014, and has remained more or less equal. There is however a clear shift from channels 1, 6 and 11 to the intermediate channels, in particular 3, 4 and 13. So comparing the 2017 measurements to those of 2014, it is clear that the distribution of channels selected has become more spread-out. So it is reasonable to assume that this recommendation was followed up, even though this can be manual operation or a changed automatic channel selection policy in the equipment.

Use 5 GHz for access

All information campaigns include the recommendation to use 5 GHz for access, mostly as multiband (2.4 GHz + 5 GHz). The measurements show a very significant increase of the number of 5 GHz APs. The measurements cannot identify whether the 5 GHz band is also used frequently. The availability of 5 GHz APs relates to multiband being the default technology solution. The measurements indicate that actually the majority of the APs are dual band. So this recommendation is at least followed up with respect to the availability of 5 GHz, though it may need attention to encourage users to move their traffic to 5 GHz as well.

Add an Access Point in case of bad performance

The measurements show no clear increase of the number of Access Points. The average number of APs observed per measurement location at 2.4 GHz has actually decreased. Adding up the number of APs per measurement location at 2.4 GHz and 5 GHz shows an increase.

There are a number of aspects to this number that should be considered.

- All or nearly all APs that support 5 GHz also support 2.4 GHz. The additional APs on 5 GHz may all be dual band APs, instead of additional APs.
- The measurements show that more APs have disabled 802.11b. As a result APs provide a smaller footprint with respect to their visibility. When considering that the geographical footprint is inversely proportional to the transmission rate of the beacon, the number of APs at 2.4 GHz has increased by circa 15%.

Overall it is realistic to assume that slightly more APs are present, in line with the recommendation.

In case of interference, change the orientation of the antenna

It is impossible to deduce the orientation of the antenna from these measurements.

In case of interference, change the location of the router

It is impossible to deduce the location of the router from these measurements.

Overall the recommended changes seem to get implemented in the WiFi solutions. Whether this is related to information campaigns is impossible to judge.

4. CONCLUSIONS

This chapter provides an overview of the most important conclusions based on this research project. The conclusions are divided in overall conclusions (paragraph 4.1) and conclusions specifically related to the research assignment (paragraph 4.2). The additional research questions are also covered in paragraph 4.2.

4.1 Overall Conclusions

- There is a **clear shift of Access Point devices from the 2.4 GHz to the 5 GHz band**. Between 2017 and 2014 the observed number of APs in the 2.4 GHz band has decreased by roughly 10%, but the number of APs measured in the 5 GHz band has increased by approximately 200%. Because the 5 GHz APs are more difficult to measure, it is expected that the ratio of 5 GHz APs compared to 2.4 GHz APs in use is even higher.
- There is a **huge growth of 5 GHz APs in city centres**. The amount of APs in the 2.4 GHz range remained roughly equal, but now the number of APs at 5GHz may be close to or equal to the number of 2.4 GHz devices.
- In 2014 nearly all APs supported the lowest data rate (802.11b), while in 2017 **roughly one third of the measured APs only support higher data rates** (802.11g/n). This improves the available throughput, while also decreasing the interference for neighbouring APs due to the shorter range.
- The measurements shows **a significant decrease in the number of APs.** It is assumed that this is a direct effect of the change of beacons at the lowest data rate (802.11b) to a higher data rate (802.11g/n). The overall number of APs in the 2.4 GHz band is likely to have increased to some extent.
- The shift to higher data rates has resulted in **a lower occupancy of the air interface,** in particular due to less beacons but also due to less other radio traffic sources. Summed for all rates the airtime taken by the beacons dropped from 18% to 14% at the measurement locations.
- The **overall WiFi throughput performance in the 2.4 GHz band is slightly improved** compared to 2014. This is expected to be due to the lower occupancy of the air interface. However, many locations still show severe congestion.

4.2 Conclusions related to Research Assignment

- **The channel distribution of the measured access points has changed** between 2014 and 2017. There is a shift from channels 1, 6 and 11 (the three non-overlapping channels) to 3, 4 and 13 in residential environments. The business park environment shows no trend in this direction, whereas City centres show this trend in a more limited way.
- The **maximum throughput of data** has also changed between 2014 and 2017. The achievable throughput on 2.4 GHz has become a bit **more extreme**: the probability of having a very bad link has increased slightly, but the probability of achieving a very good link has increased considerably. Throughput on 5 GHz is nearly always very good. Only in city centres has the 5 GHz performance deteriorated slightly.
- Provide an **overview of the spectrum usage in both WiFi bands**, regardless of protocol or technology - the spectrum measurements show that the 2.4 GHz band is filled with a lot of traffic, most of it broadband transmissions like WiFi. In certain spots there is interference from non-WiFi sources. These interference sources do not always follow the rules applicable to this frequency band. On the 5 GHz band there still is a lot of capacity available, but in busy areas performance has suffered slightly.

Additional research questions:

- **Mesh-technology**: Mesh networking was only seen on less than 1% of all stations observed.
- The **fraction of APs that is operational in de DFS frequencies** has increased from 30% in 2014 to nearly 50% of all 5 GHz APs. APs using channels 52 and 100 represent over 40% of all APs using the DFS frequencies. In particular the high use of channel 100 suggests that many 5 GHz APs use this as their default channel.
- The **effectiveness of information campaigns** is very difficult to measure, as its effect cannot be distinguished from the effects of replacement of equipment and technology or optimizations by operators. What is measured is that AP channels have been changed and there is a huge growth of 5 GHz APs.
- **Extension of the measurement locations to other large cities** – the city of Utrecht was added to the measurements, the locations where both residential and city centre type. The results were comparable to Rotterdam in many aspects.
- **Analysis of the WiFi router brands and types** - Business Areas show a dominant presence of high-end manufacturers, while residential areas are dominated by equipment provided by ISPs. When additional APs are installed (as is the case in many households), they are normally from manufacturers focused on the consumer market. The city centres show a curious mix of business grade and consumer grade equipment.

5. RECOMMENDATIONS

Considering the measurement campaign and the analysis, the following recommendations are given for the government, the market parties and for future measurement campaigns.

Government

1. Scanning APs and processing their information has shown to be an appropriate measurement method. Future measurement campaigns are recommended to be based on AP scanning.
2. The 2.4 GHz band contains competing technologies that do not share the spectrum evenly. It is recommended to see if the multiple access rules for the various technologies can be (partly) harmonized. WiFi always does Listen Before Talk (LBT), while Bluetooth and many drone transmissions simply transmit on a chosen channel. Perhaps WiFi also should be allowed to transmit if the signal to noise ratio (SNR) is enough for a good connection, even when other signals are present.
3. The measurements should be executed more regularly and possibly in more locations to improve the representativeness of the measurements and the analysis of the trends.

Market parties

4. The impact of beacons at 2.4 GHz remains large. This impact may be reduced when the default beacon interval time would be increased. The project recommends to investigate the possibility of letting the beacon interval time to be increased to at least 200 ms.
5. Backward compatibility to 802.11b still seems to be supported in many cases. This option should be discouraged as much as possible.

Future measurement campaigns

6. The measurement campaign is a snapshot of limited size. The accuracy of the results can be improved by creating a continuous measurement method, and by increasing the number of sites.
7. The measurement set-up should evolve with the ongoing changes to WiFi technology.
8. A measurement campaign should be combined with market information to improve the information on what is actually in use.
9. Throughput performance is currently measured at two static channels (11 and 44), which could be improved by executing measurements at a larger variety of channels.
10. The analysis of mesh networking may be improved by modifying the measurement method. For defining this method it is recommended to analyze commercial mesh product offerings on identifiable radio characteristics.

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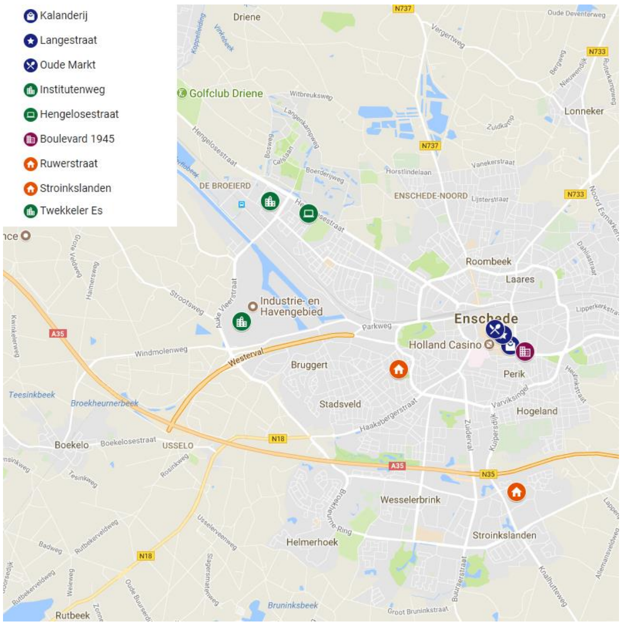
APPENDIX A MEASUREMENT LOCATIONS

The below locations are selected for the 2017 measurements. The locations are the same as in 2014 with 20 locations added in the city of Utrecht Table 6 shows the categories and subcategories of the locations.

Table 6 Categories of locations

1 City centre	a) Shopping Area	b) Shopping Mall	c) City centre
2 Business Parks	a) Outdoor		b) Indoor
3 Residential, high-rise			
4 Residential, low-rise	a) Houses in a row		b) Semi-detached



Enschede:

Location 1.1a: Kalanderstraat/De Heurne, Stadsgravenstraat

Location 2.1b: De Klanderij

Location 3.1c: Oude markt

Location 4.2a: Institutenweg/Marssteden

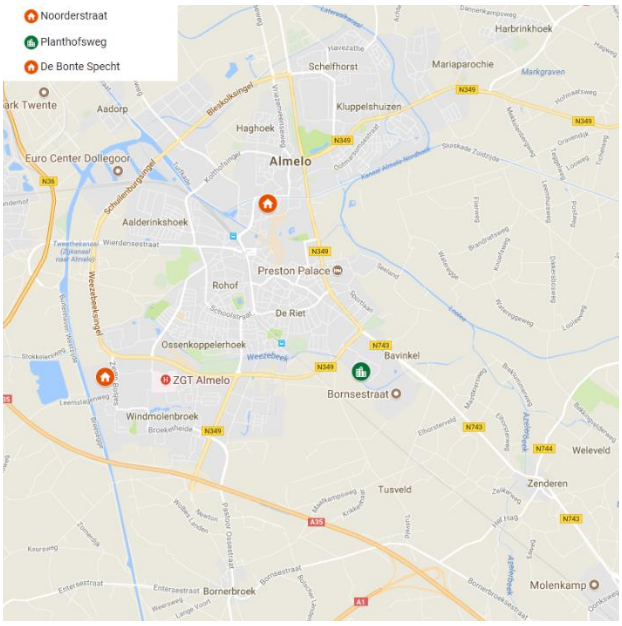
Location 5.2b: Hengelosestraat

Location 6.3a: Boulevard 1945

Location 7.4a: Munsterstraat, Ruwerstraat

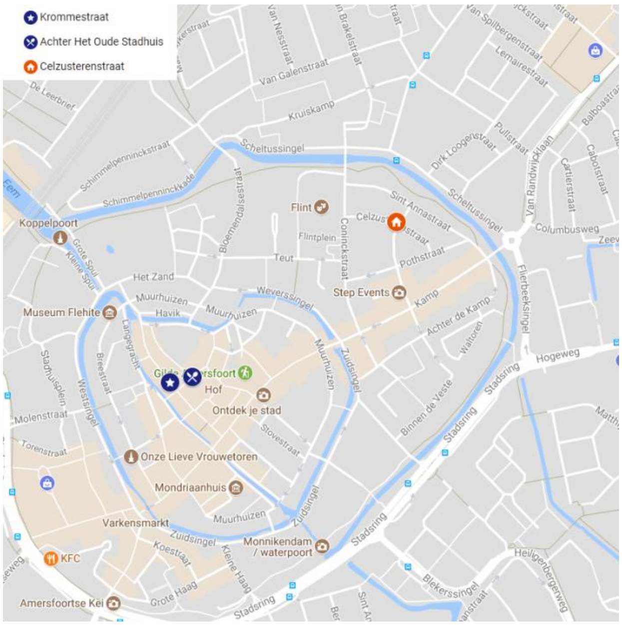
Location 8.4b: Stroinkslanden

Location 30.2a: Twekkeler Es



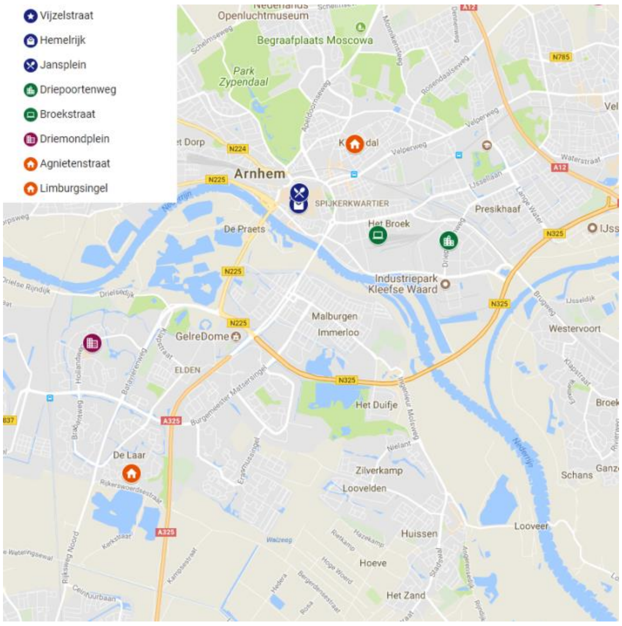
Almelo:

Location 9.4a:	Noorderstraat, Asterstraat
Location 31.2a:	Planthofsweg, Edisonstraat, Voltastraat
Location 32.4b:	De Bonte Specht De Emoe, De Condor



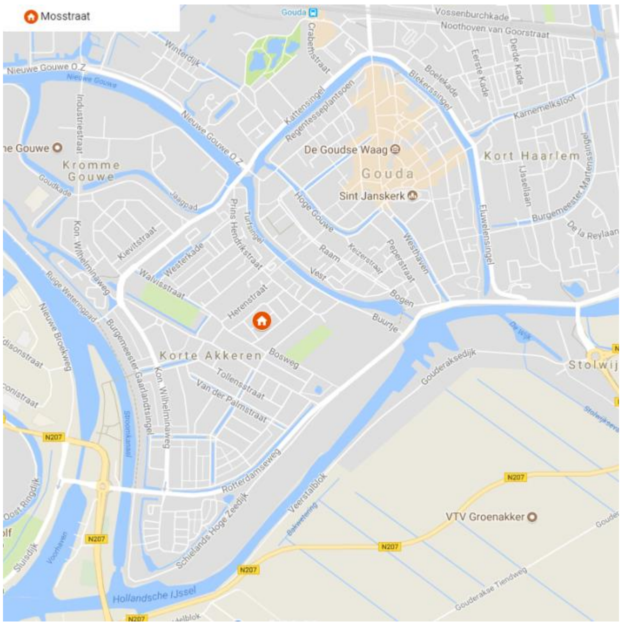
Amersfoort:

Location 10.1a:	Langestraat, Kommestraat
Location 11.1c:	Achter het oude stadhuis
Location 12.4a:	Celzusterenstraat, Kruiskamp



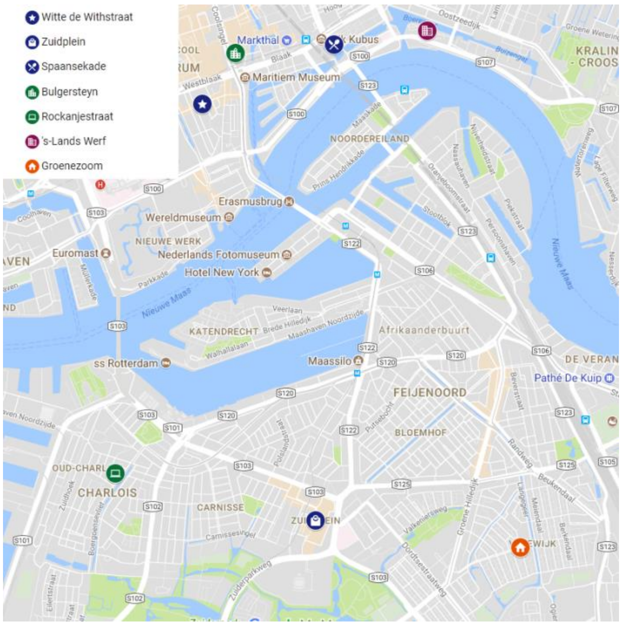
Arnhem:

Location 13.1a:	Rijnstraat/Vijzelstraat, Bakkerstraat
Location 14.1b:	Winkelpassage Het Hemelrijk
Location 15.1c:	Jansplein, Rijnkade
Location 16.2a:	Driepoortenweg
Location 17.2b:	PEJA (Broekstraat 32, Arnhem)
Location 18.3a:	Driemondplein, Shipholplein, Gorinchemstraat
Location 19.4a:	Agnietenstraat, Pijlkruidstraat
Location 20.4b:	Limburgsingel, Obrechtstraat



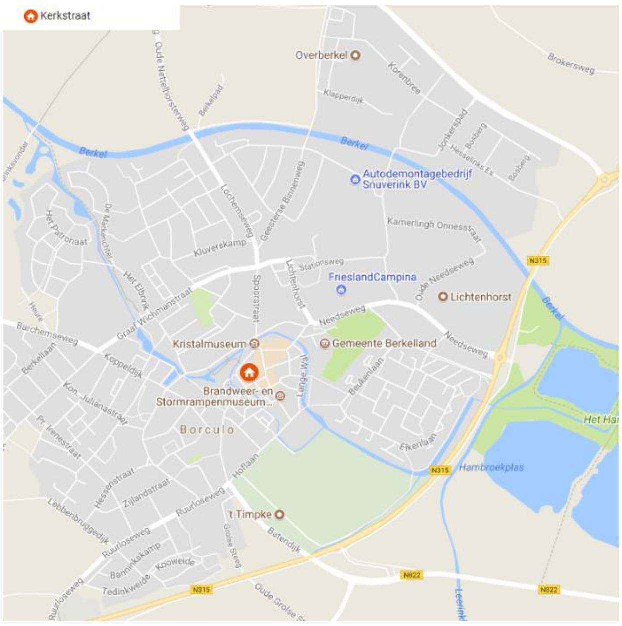
Gouda:

Location 21.4a:	Mosstraat, Thorbeckelaan



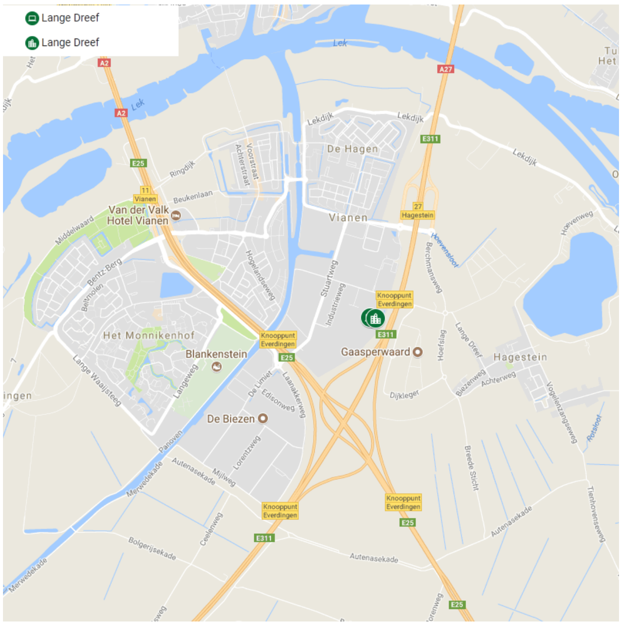
Rotterdam:

Location 22.1a:	Hoogstraat, Witte de Withstraat
Location 23.1b:	Winkelcentrum Zuidplein (Zuidplein Hoog 420)
Location 24.1c:	Spaanse Kade, De Meent
Location 25.2a:	Bulgersteyn, Blaak/Wijnstraat, bedrijventerrein Noord-West
Location 26.2b:	ECO (Rockanjestraat 13). Cool (Eendrachtsstraat 150)
Location 27.3a:	's-Lands Werf, Strevelsweg
Location 28.4a:	Groenezoom, Gerard Scholtenstraat, Opzoomerstraat



Borculo:

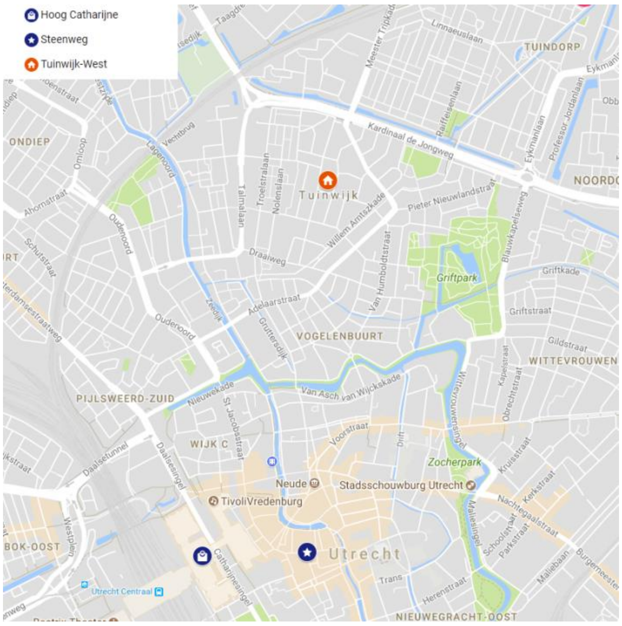
Location 29.4b:	Kerkstraat



Vianen:

Location 33.2b: Lange Dreef

Location 34.2a: Lange Dreef



Utrecht:

Location 35.1b: Hoog Catharijne

Location 36.1a: Steenweg

Location 37.4a: Tuinwijk-West