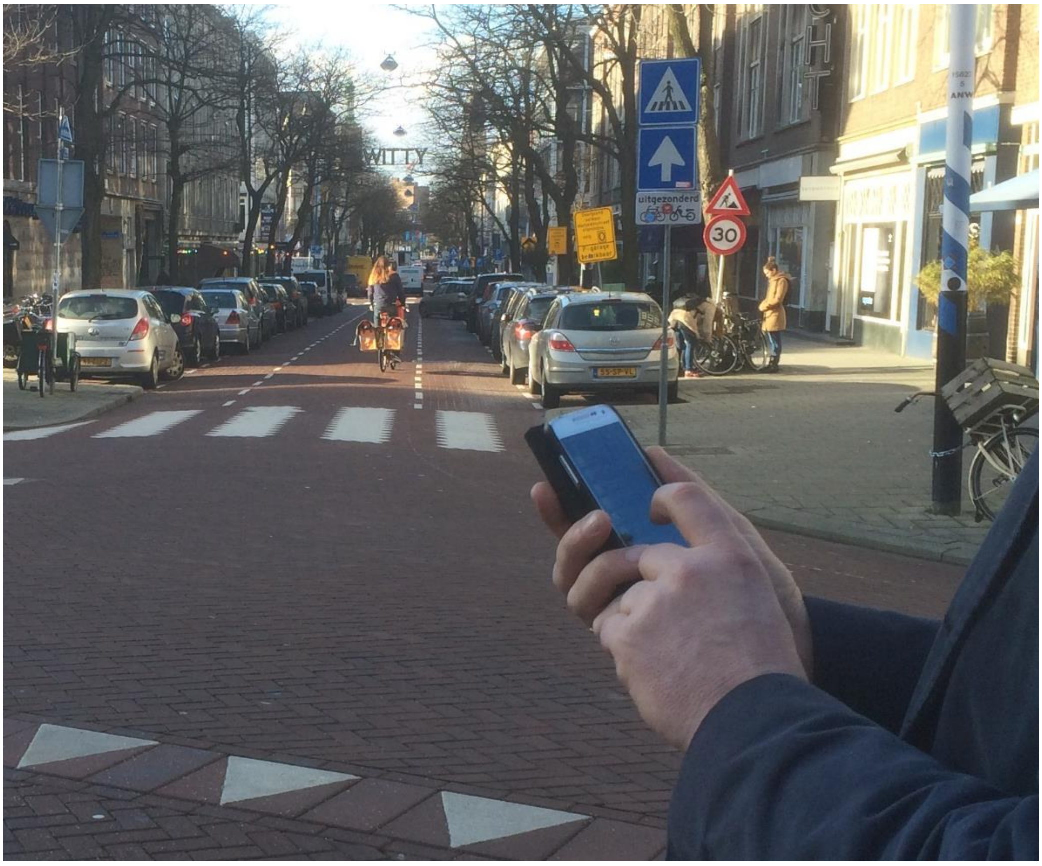
Research into the License Exempt Spectrum of the Netherlands

Version 1.0, February 26, 2015



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ABSTRACT

There have been some concerns about the rapid growth of WiFi networks. The use of this radio technology is important to society as a whole.
Radiocommunications Agency Netherlands (Agentschap Telecom) has commissioned Strict Consultancy and FIGO to perform research into the usage of the 2.4 GHz and 5 GHz bands. An investigation was performed to determine whether congestion and/or interference are present. Measurements used Radio Frequency scanning (overall usage and interference levels), Access Point scanning (number of Access Points), throughput measurements and frame sniffing. Measurement locations were public areas in City Centers, Business Parks and Residential Areas (both low rise and high rise locations). Measurements at more than 180 locations were used as input.

There are locations where available capacity (data throughput) is severely limited and there is serious congestion. This is most often the case in City Centers (more than 25% of the locations), Residential Areas with houses in a row (more than 25%) and in residential high rises (more than 57% of the test locations).
In a number of locations high levels of interference were measured with corresponding lower data throughput. Especially in Shopping Malls the interference levels and number of active networks were extreme (on average more than 50 Access Points were found), causing severe performance problems on the 2.4 GHz band.
In locations with relative high usage, the Access Points are often evenly distributed over the channels 1, 6 and 11. However, this does not prevent interference and congestion.
The measurements show significant number of networks (SSIDs), from public WiFi operators like UPC, Ziggo and KPN (FON). This larger number of SSIDs causes more overhead.

Overall, the capacity of WiFi is much less than advertised by the standard. Sometimes users expect 300 Mbit/s because they have an 802.11n 300 Mbit/s Access Point. However the radio circumstances are seldom ideal, transmission time is needed for control frames, transmission time is needed to handle random channel access and transmission time needs to be shared with all other users in the surrounding area that are on the same channel. The resulting data speed is perhaps only 10 – 20% of the advertised bandwidth even when there is little congestion.

Due to backwards compatibility and the high number of Access Points found in nearly all test locations, the available transmission time is reduced to a large extend. Up to 37% of the airtime was used for beacon signals of Access Points. It is recommended to avoid backward compatibility to 802.11b as much as possible in heavy traffic environments.
It is also recommended to investigate how the beacon recurrence rate (normally 10x per second) can be lowered. This could release more airtime for data transport.

Overall, it is recommended to use important services only on the 5 GHz band, which has currently much less interference and more available channels.

It is also recommended to regularly investigate the state of the license exempt spectrum to monitor traffic growth and number of networks. Further investigation should be done to see how backwards compatibility can be phased out and interference from other WiFi networks can be reduced, perhaps by lowering transmission power. It is recommended to add more detailed analysis to this measurement campaign to better understand the behavior of state-of-the-art WiFi in practical scenarios.

1 INTRODUCTION

The Radiocommunications Agency Netherlands (Agentschap Telecom) has an important public role with regards to radio technology and frequency usage. They commissioned Strict and FIGO to perform public measurements on the 2.4 GHz and 5 GHz frequency bands. These frequency bands can be used without a license (license exempt) and are mostly used for WiFi internet access in public and private areas. Agentschap Telecom initiated a research project to better understand the usage of these frequency bands and if there is congestion in certain areas.

1.1 Background

In the past couple of years many new devices communicate via WiFi technology. Many consumers have added WiFi access points to their households and also offices are using WiFi for LAN access. Also in shops WiFi is being used for all sorts of business functions. Many people carry more than one WiFi capable device. 70% of all internet traffic is estimated to be transmitted over WiFi networks, and the amount of data is roughly doubling every year [ref1]. At the same time, the 2.4 GHz band is also used for Bluetooth, microwave ovens and wireless video links, etc.
The question has arisen whether the license exempt bands are still providing the right facilities in the public and private space, because some problems have been reported. Agentschap Telecom has also warned the public for problems due to the rapid growth [ref1].

Over the last years, WiFi operators like KPN, UPC and Ziggo have started public services. Also Mobile Network Operators are looking into using WiFi for 'data-offload', to reduce the data traffic in the 3G and 4G networks. This can also impact capacity and congestion of the WiFi bands.

1.2 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.

To investigate the current status, measurements should be performed in the following area types:

- Public Areas in City Centers
- Business Parks with groups of companies
- Residential Areas with high rises / flats / apartments
- Residential Areas with houses in a row / semi-detached

The following supporting questions have been added to the assignment:

1. Which measurement setup is able to answer the research questions in the best possible manner, taking into account current scientific knowledge and best practices?
2. Which metrics are the most relevant to assess the status of an area type?

- Spectrum occupancy
- Channel utilization
- Frame rate / retry rates
- Number of users/nodes
- User/device density
- Data traffic
- Type of equipment or device mode (802.11a/b/g/n/ac etc.)

3. Based on the measurements, what are the results per area type of the 2.4 GHz and 5 GHz bands?
4. What is the measured impact on the area types and 2.4 GHz / 5 GHz frequency bands of public WiFi-operators like Ziggo, UPC and KPN?
5. Which important interference types of WiFi can be derived from the measurements (MAC and PHY layers)?
    - Non WiFi interference (Bluetooth, microwave, videolinks, etc.)
    - Self-interference (WiFi -> WiFi)
    - Congestion/capacity
    - Legacy systems (for example older standards)
    - Hidden nodes
    - Overhead (protocol/beacons)
    - User configuration (suboptimum settings like channel selection, etc)
    - Public WiFi/WiFispots
6. How is the 5 GHz band developing compared to the 2.4 GHz band? How many nodes can be found in the 5 GHz band compared to the 2.4 GHz-band? What is the actual use of the 5 GHz band in comparison with the 2.4 GHz band?

1.3 Strict and FIGO

This project was carried out jointly by Strict and FIGO.

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.

1.4 Report structure

In the following chapter the research method is explained and related to the assignment questions. The measurement setup is explained, as well as the chosen measurement locations.
In chapter 3 the measurement results are shown and analyzed. Per area type the results are presented. A selection of the most interesting information is provided.
In chapter 4 conclusions are made, based on the research data and measurements. The assignment questions are also discussed. Chapter 5 provides recommendations on the use of WiFi in the 2.4 GHz and 5 GHz bands and further avenues for investigation.

2 RESEARCH METHOD

At the end of October 2014, the research assignment was given to Strict and FIGO after a tender process. All measurements had to be performed within 2 months to meet the goals of assignment. This created some challenges, because the ambitions of the research assignment were high. It was decided to make measurements in public areas and to perform measurements in 150 – 200 unique locations, while using 15 – 20 minutes for each test.

In this chapter the way the research was executed is described. First some important aspects of WiFi connections are described. Then the measurement methodology is discussed, in relation to the research assignment. In paragraph 2.3 the different test cases and the test setup are described. In paragraph 2.4 the list of selected locations for the measurements is presented. The tests are designed to provide answers to current usage of WiFi in the different area types, the level of congestion and possible interference sources. The last paragraph describes spectrum occupancy and the qualification of data throughput used in the results.

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. WiFi uses a shared medium which is on the 2.4 GHz and 5 GHz bands. Each band has a number of channels. In the 2.4 GHz band, these channels are partly overlapping, see figure 2.1. Each AP can transmit one or more networks, each network is identified by a SSID (Service Set IDentifier) on a certain channel.

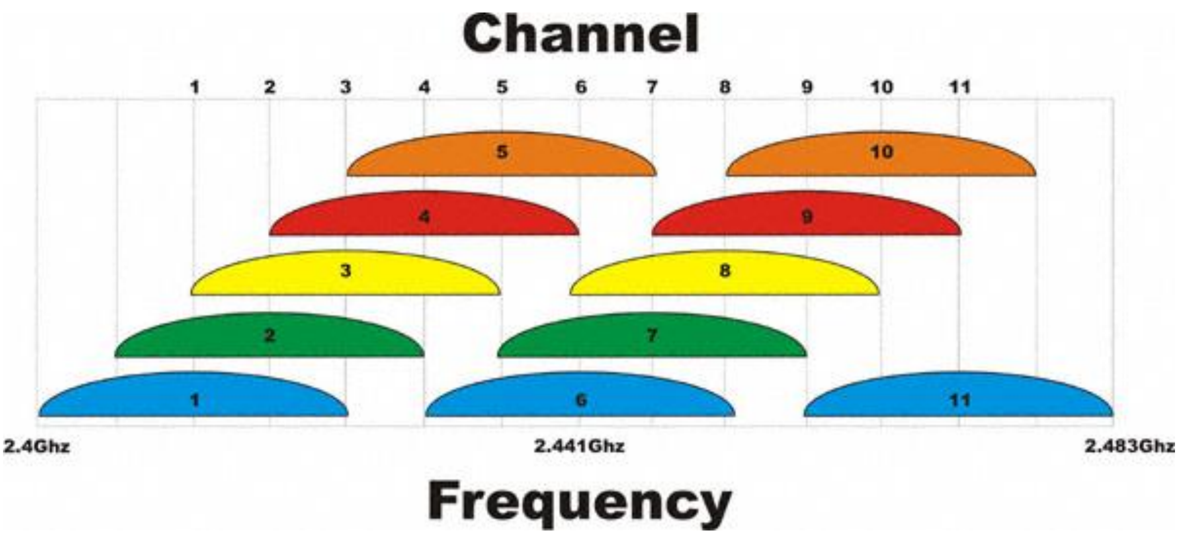

Figure 2.1 – Overlapping WiFi channels 2.4 GHz (source: www.odessaoffice.com)

When clients want to transmit or receive data, they access the radio channel without scheduling. Currently there are several WiFi standard versions being deployed that differ in their physical layer specification, so in the way they occupy the radio channel, namely 802.11a, 802.11b, 802.11g, 802.11n and 802.11ac. A short overview of the standards is given in Table 2.1.

Standard	Gross Data rate	Band	Year Approved
802.11a	54 Mbit/s	5 GHz	1999
802.11b	11 Mbit/s	2.4 GHz	1999
802.11g	54 Mbit/s	2.4 GHz	2003
802.11n	600 Mbit/s	2.4 & 5 GHz	2009
802.11ac	>1 Gbit/s	5 GHz	2013

Table 2.1 – IEEE 802.11 Wireless standards

802.11b and even 802.11a/g are sometimes referred to as legacy standards, because they are being replaced by 802.11n and 802.11ac equipment.
The Physical layer data rates (gross) of 802.11b and 802.11g (similar to 802.11a) are shown in Table 2.2.

Standard	Radio Data Rate, Mbits/s	Modulation scheme and coding rate
802.11b	1	DBPSK
	2	DQPSK
	5.5	CCK+DQPSK
	11	CCK+DQPSK
802.11g	6	BPSK 1/2
	9	BPSK 3/4
	12	QPSK 1/2
	18	QPSK 3/4
	24	16QAM 1/2
	36	16QAM 3/4
	48	64QAM 2/3
	54	64QAM 3/4

Table 2.2 Radio data rates and modulation for 802.11b & 802.11g

In all 802.11 standards, there are different coding rates for the different modulation schemes. This allows for adaptive modulation and coding, related to radio conditions: when there are too many errors in the transmission, the modulation scheme and/or coding rate is lowered to improve robustness.
A summary of the gross data rates of 802.11n are shown in Table 2.3. The higher data rates are achieved by using higher modulation schemes than 802.11a/g and wider channels (40 MHz). This

is only advantageous when there is little interference. 802.11n modulation can be used both on the 2.4 GHz band and on the 5 GHz band. In the 2.4 GHz band it is only possible to deploy one 40 MHz channel without overlap. 802.11n also enables to lower the Guard Interval (GI) between transmitted packets (the modulated bits). The throughput can be higher in ideal circumstances. The highest data rates are achieved by using more than one spatial stream, were several parallel connections are made through multiple antennas for both AP and client. However, not many client devices have multiple antennas. Experience from other mobile technologies has shown that doubling the number of antennas does not double the data rate. A 50% increase is seen as more realistic.

MCS index	Spatial streams	Modulation type	Coding rate	Gross Data rate (Mbit/s)			
				20 MHz channel		40 MHz channel	
				800 ns GI	400 ns GI	800 ns GI	400 ns GI
0	1	BPSK	1/2	6.5	7.2	13.5	15
1	1	QPSK	1/2	13	14.4	27	30
7	1	64-QAM	5/6	65	72.2	135	150
15	2	64-QAM	5/6	130	144.4	270	300
23	3	64-QAM	5/6	195	216.7	405	450
31	4	64-QAM	5/6	260	288.8	540	600

Table 2.3 Data rates for 802.11n (source: http://en.wikipedia.org/wiki/IEEE_802.11n-2009)

With 802.11ac, the maximum throughput is increased even more. This is realized by using higher modulation schemes like 256 QAM (also used in cable modem standard DOCSIS) and wider channels of 80 and 160 MHz. These wide channel bandwidths are only possible in the 5 GHz band. Table 2.4 shows the modulation and data speeds of 802.11ac. By using multiple antennas on both AP and client, a number of Spatial Streams can be combined to create even higher data rates.

802.11ac - Theoretical throughput for single Spatial Stream (in Mbit/s)										
MCS index	**Modulation type**	**Coding rate**	**20 MHz channels**		**40 MHz channels**		**80 MHz channels**		**160 MHz channels**	
			800 ns GI	**400 ns GI**	**800 ns GI**	**400 ns GI**	**800 ns GI**	**400 ns GI**	**800 ns GI**	**400 ns GI**
0	BPSK	1/2	6.5	7.2	13.5	15	29.3	32.5	58.5	65
1	QPSK	1/2	13	14.4	27	30	58.5	65	117	130
9	256-QAM	5/6	N/A	N/A	180	200	390	433.3	780	866.7

Table 2.4 Data rates for 802.11ac (source: http://en.wikipedia.org/wiki/IEEE_802.11ac)

The highest modulation schemes are only useful when the Signal to Noise Ratio is high and there is very little interference. Typical WiFi systems use adaptive modulation and coding to arrive at the modulation scheme that has a just sufficient Signal to Noise Ration. Most of the time the selected modulation scheme is below the maximum.
In addition realistic data throughput of the different standards and modulation schemes is significantly less than the physical (gross) data rates. Some time is needed for beacons (letting users know the WiFi Access Point is active), acknowledgements, retries, etc. In congested situations, the WiFi signal can contain up to 70% management frames. More information can be found here [ref 2].
According to the thesis research “Application-oriented Link Adaptation for IEEE 802.11” [ref 3], Figure 2.2 (see below) shows the maximum throughput for 802.11a for a given Signal to Noise Ratio (SNR). This is the same for 802.11g, which is the 802.11a standard on the 2.4 GHz band.

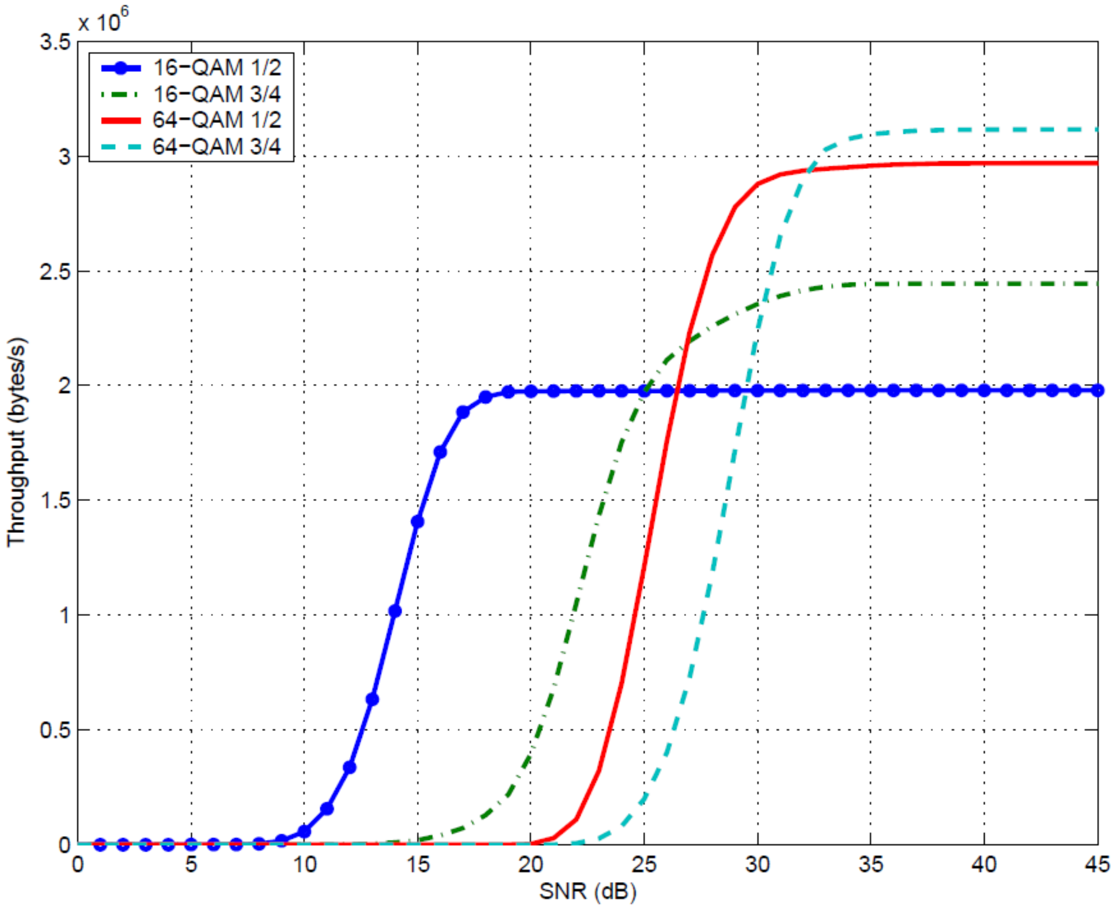

Figure 2.2 Maximum Throughput versus SNR for 802.11a [ref 3]

Based on the highest modulation scheme (64QAM ¾), the maximum throughput of an 802.11g Physical layer 54 Mbit/s carrier is only 3.1 Mbyte/s. This is calculated to 24.8 Mbit/s in ideal circumstances (3.1 Mbyte/s * 8 bit/byte = 24.8 Mbit/s).

Other sources [ref 4] state 23 Mbit/s as the highest possible speed on 802.11g. The highest measurements in this research test setup were around 21 Mbit/s, realized in rural residential areas with very little spectrum occupancy.
Similar limitations apply to 802.11n and 802.11ac. As air interface access is time shared, occupancy of the air-interface by legacy standard based transmissions have a significant impact also on state-of-the-art WiFi systems.
Especially in a mixed mode setup (which is default on most APs), backwards compatibility with older standards like 802.11b reduces the maximum possible data rates. For backward compatibility for example the beacon signal is transmitted on the lowest data speed, namely 1 Mbit/s. When devices connect using 802.11b and 11g, this has a relative large impact on the available throughput for 802.11n. For a given amount of data, the legacy systems (802.11b and 802.11g) need much more time for transmissions. This leaves less time for 802.11n transmissions in any setup with an AP and a combination of different devices.
In a busy environment, there is even less time for transmissions because the channel is a shared with other APs and users. This also increases the amount of management frames, needed to prevent collisions and handle retransmissions. And because of higher interference by other networks, the Signal to Noise Ratio is often not good enough to use higher coding schemes, reducing the possible throughput even more. This is summarized in Figure 2.3.

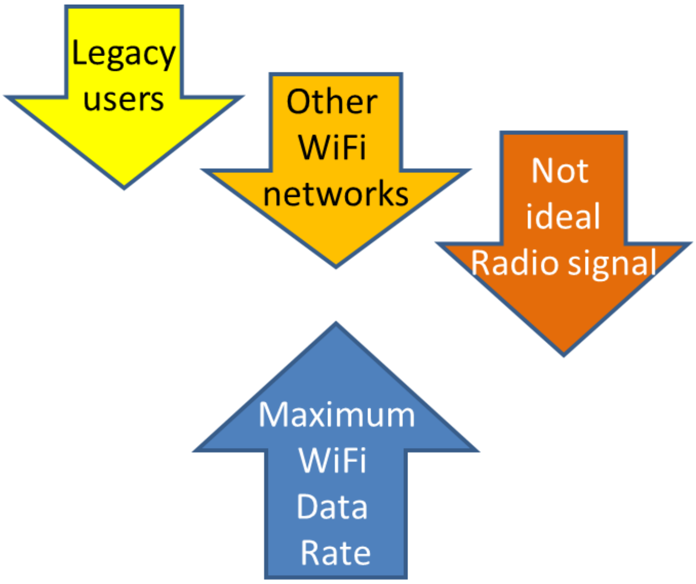

Figure 2.3 Impact on Maximum Data Rates

During this research project, measurements are performed using a WiFi radio in monitor mode, where the device measures the radio conditions of the direct surroundings. The output is related to both physical layer (PHY) and data link layer (MAC). In the physical layer, the radio measures the actual signal levels. Based on the signal levels, WiFi then determines if the medium is occupied or free.

The data throughput of the WiFi network is depending on the conditions of the physical layer. This is tested with the AP reference measurement, where the actual data throughput is determined. The data throughput can be significantly less due to congestion and capacity limitations, as will be shown in chapter 3.

2.2 Research Methodology

Before the investigation could start, the measurement methodology was determined.
WiFi radios function by using CSMA (Carrier Sense Multiple Access). A WiFi radio will always observe the radio spectrum for frames and for radio signals before starting transmitting. According to the Harmonized European Standard ETSI EN 300 328 V1.8.1 (2012-04) [ref 5], WiFi equipment will check using energy detection during a Clear Channel Assessment (CCA) period of at least 20 µs. The energy detection threshold for the CCA shall be proportional to the transmit power of the transmitter: for a 20 dBm e.i.r.p. transmitter (which is used in WiFi), the CCA threshold level (TL) shall be equal or lower than -70 dBm/MHz. This threshold was added to the ETSI standard after input from the Radiocommunications Agency Netherlands several years ago.

For CSMA it is only important whether the medium (the radio carrier) is occupied or free. This is one of the most important aspects of determining available capacity. If the medium is occupied, the WiFi radio will not transmit. The reason the medium is occupied or the source of the signal is of no concern to the WiFi radio. The measurement methodology is based on this idea.

This research project was started to investigate the risks of congestion and interference in the 2.4 GHz and 5 GHz frequency bands. Six important supporting questions are part of the research assignment, dealing with measurement setup, relevant metrics, results per area type, public WiFi operators, interference and comparison between 2.4 GHz and 5 GHz band. In the following subparagraphs these aspects are discussed.

2.2.1 Measurement Setup

The first question in the research assignment is which measurement setup is able to answer the research questions in the best possible manner.
Based on practical experience of many WiFi applications, 2 major aspects are determined: spectrum occupancy and actual throughput.
The first set of measurements determine how a WiFi radio sees the spectrum occupancy.
Therefore a scan is made on radio channels for:

- RF signal levels (all channels);
- Number of unique MAC addresses;
- RSSI (Received Signal Strength Indication) per MAC address;
- Number of unique SSIDs, especially the number SSID's from KPN, Ziggo and UPC;
- Number, type and size of the visible frames (protocol type, frame type).

For the second aspect, it is determined how much data WiFi can still be transmitted on the shared medium. To do this, a connection is made between an AP and a client. Using a predefined amount of time, data is transmitted over this link and the average throughput is determined.

2.2.2 Relevant Metrics

The second assignment is to determine which metrics are the most relevant to assess the status of an area type. In this research, due to both the short preparation time and the broad scope of the research questions, a decision was made to perform multiple types of measurements and gather various different metrics. The different metrics are discussed shortly here:

- **Spectrum occupancy**: WiFi uses the spectrum based on CSMA. The medium is either occupied or free. Analyzing the medium is then a valid metric to determine spectrum occupancy or spectrum utilization. As described in the previous paragraph, the number of APs, the amount of visible frames and the available bandwidth (throughput) are used to determine the spectrum occupancy.
- **Channel utilization**: Sampling of the number, type and size of frames provides an image of what is being transmitted. Also the possible additional throughput is used to determine channel utilization.
- **Retry rate**: Transmitted frames with the retry bit on '1' provides information on retries. This is not a clear metric, because more retries do not automatically mean that the system is less efficient. In an efficient setup, there is typically a number of retries. The system is always trying to increase the radio data rate by changing to a higher modulation scheme (see Table 2.1). There is typically a balance between high transmission speed and number of retries, different vendors of WLAN equipment have different implementations of the algorithms. This metric could be used, but it is not used in this research setup.
- **User/device density**: The number of unique MAC addresses in scans provides the right information. However, previous experience has shown that relative long measurement periods are needed, because some devices only transmit once every several minutes. Also measuring from public areas (e.g. on the street), it is expected that relative more APs than client devices would be found as APs are installed for coverage and have a longer reach. This metric is reported, but the information is expected not to be very useful.
- **Data traffic**: Analysis of the frame type provides information on the different types of traffic. Frame type (management, control, data frames), data rate and amount of frames/bytes can be quantified. This metric is reported and useful.
- **Type of equipment or device mode (a/b/g/n/ac):** The type of equipment is not measurable from the radio side. It can be related to the vendor code of the MAC addresses, but this does not provide a complete picture. It can be determined by interviewing users. This is outside the scope of this research.
- **Round Trip Time:** When packets are transmitted from a client over a WiFi link to the AP and back, a certain amount of time is needed. When there is some delay, the medium is partly occupied. When measured a number of times (as is done here during each measurement, using information of the data throughput test), the median value is reported as an supporting indication of how occupied the medium is.

2.2.3 Assessment of the 2.4 GHz and 5 GHz bands

The metrics are used to assess the usage of the 2.4 GHz and 5 GHz bands. By performing the measurement of both bands at the same locations, the results can be compared. But because of the different propagation characteristics, a complete 1-to-1 comparison is not possible. It was decided not to measure 802.11ac usage, but to measure the overall Radio Frequency use of the 5 GHz band. The 802.11ac standard is only used on the 5 GHz band and products are only now becoming mainstream. The installed base however is still very limited.

2.2.4 Measuring WiFi-operators

The public WiFi networks of KPN, Ziggo and UPC can be measured by looking for their specific SSIDs. Ziggo and UPC have fixed geographical coverage based on their cable networks. A comparison between these two is possible. A comparison with KPN is not possible in specific regions (because of their nationwide coverage), but it is possible by looking at the number of Access Points with the KPN SSIDs. The public WiFi networks are created by adding a second SSID to the AP, which are also measured in the AP scan. The impact of these networks is determined through the number of APs found.

2.2.5 Determine sources of interference

The measurements are able to determine certain sources of interference.

- Non WiFi sources: can be seen as increased RF levels and certain RF patterns.
- Self-interference can be assumed from sampling the number of retries, but this is not a simple metric and is not conclusive (see paragraph 2.2.2, 3rd bullet).
- Congestion/capacity can be determined based on the result of CSMA status analysis.
- Legacy systems cannot be specifically determined in the measurements, but legacy operating modes can be determined.
- The hidden nodes can be assumed in an indirect way by looking at retries and acknowledgements, but this is not conclusive (see paragraph 2.2.2. about retries). Individual transmissions would have to be analyzed much more in depth over longer periods.
- Overhead is visible by analysis of frame types. Backwards compatibility of 802.11n with legacy systems increases the amount of overhead because 802.11n sends RTS/CTS to inform legacy systems that it will transmit.
- User configuration can be partly determined, by looking at the distribution of traffic on the different channels.
- Public WiFi/WiFi spots are visible by analyzing the SSIDs they broadcast.

2.2.6 Developments in 2.4 GHz compared to 5 GHz

The measurements of the number of Access Points in the 5 GHz band can be compared to the number of Access Points found in the 2.4 GHz band. But measuring in public areas (for example parked on the street) will automatically show less 5 GHz nodes because of the relatively long distance to the Access Points (located indoor). The maximum range of WiFi in the 5 GHz band is significantly lower than in the 2.4 GHz band, a direct comparison based on this investigation is not possible.

2.3 Measurement Configuration

To answer the research questions, several different measurements tests have been used. The following measurements have been performed:

- Radio Frequency scanning using a laptop with a WiSpy dongle;
- Scanning of Access Points using a laptop with 802.11a/b/g/n capabilities;
- Logging of frame types (Beacons, management and data) using logger with 802.11a/b/g;
- Testing available capacity by measuring throughput using 802.11a/g;

The measurement setup consists of a combination of hardware and software, using scripts to run all tests in the same manner. All measurements were first tested in some pilot locations. These tests were performed to verify the measurement equipment setup, the measurement scripts and the measurement results.

The following channels were used for the different measurements:

- WiSpy RF Scan: all channels
- AP scan: all channels
- Throughput test (reference AP) 2.4 GHz: 2462 MHz (channel 11)
- Throughput test (reference AP) 5 GHz: 5220 MHz (channel 44)
- Frame logging (sniffing) 2.4 GHz: 2412 MHz (channel 1)
- Frame logging (sniffing) 5 GHz: 5220 MHz (channel 44)

During frame logging, by sniffing the radio frames, a fixed amount of bytes were stored to capture the header information. In some cases a small portion of the user data (a number of bytes) was captured. However, this user data is incomplete and also encrypted.
Most of the measurements were performed in and around a vehicle. Equipment was mounted in the back of the car (see figure 2.4).

The measurement setup used 2 Access Points, one for 2.4 GHz and one for 5 GHz. An 802.11a/b/g radio card was used with 20 dBm maximum output, configured at 19 dBm output. A 20 dB attenuator was used for 2.4 GHz, a 10 dB attenuator was used for 5 GHz. In both cases a 5 dBi antenna was used.

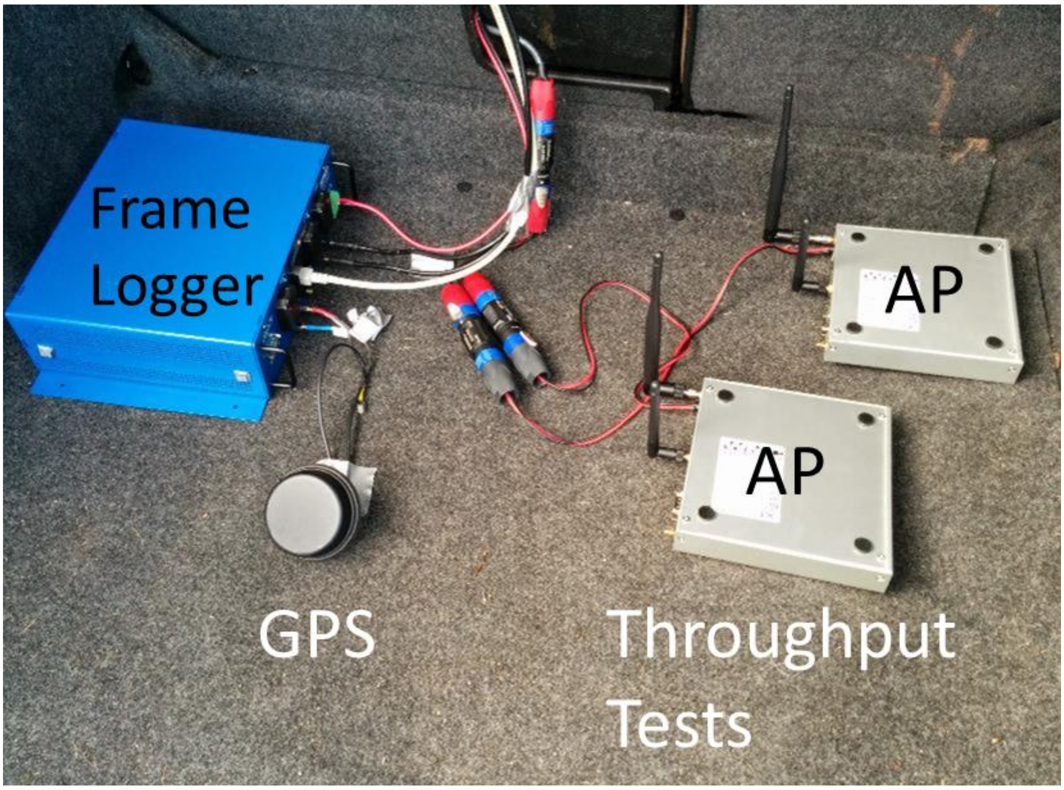

Figure 2.4 Equipment setup in vehicle

For the throughput test, a fixed distance of 10 meters was kept to the vehicle, using laser measurement. The APs are also attenuated, resulting in a signal level of -65 dBm during the reference measurements.

A typical measurement is shown in figure 2.5. By using the attenuation and the 10m distance, impact of other APs and clients can be measured. When parked in urban areas, other WiFi connections will definitely impact maximum throughput.

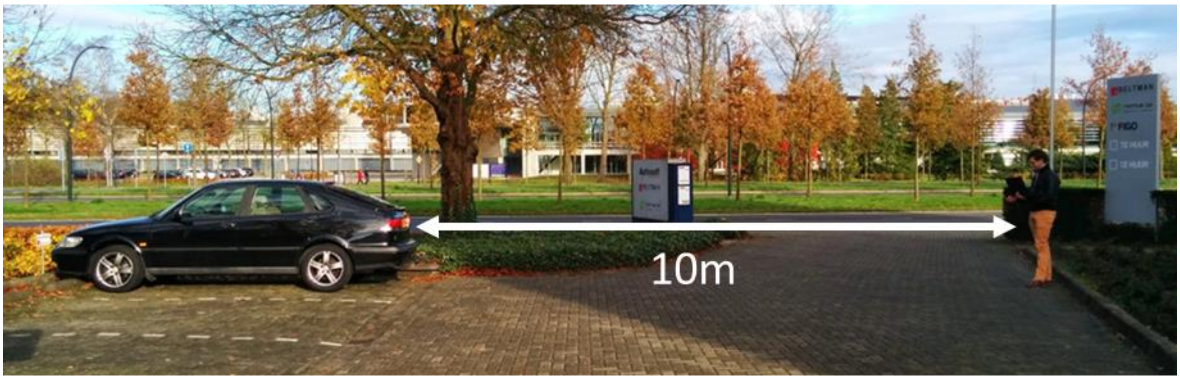

Figure 2.5 Data throughput test with 10 meter distance

For some indoor tests (Shopping Mall, Business Park), a mobile configuration was made. This setup did not include the sniffing of all frame types, because of the weight and size of the logging node. For the data throughput, a 20 dB attenuator was used on the Access Point to simulate a longer distance between the Access Point and laptop.

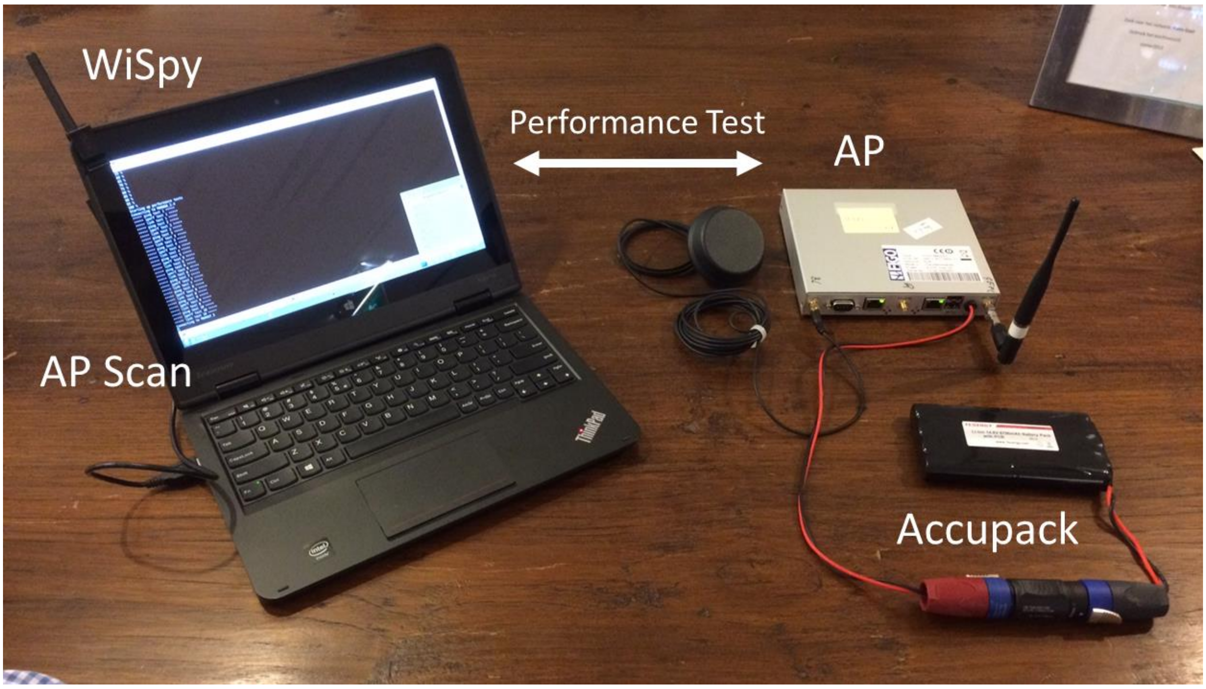

Figure 2.6 Portable test setup

2.3.1 Hardware

The hardware used for the measurements, include FIGO Mobile Nodes. These nodes have a standard WLAN radio that can function as AP, client and scanning device.

Figure 2.7 FIGO Mobile Node

The FIGO Mobile Node is a small portable computer platform, running a version of Linux OS. The WLAN module is controlled by the OS. It can be used for many specific functions and it provides a lot of detailed information. The FIGO node is used in many different deployments and is fully proven in public configurations for traffic measurements and the like.

Because the WLAN module can function as AP, client and scanner, it is possible to have different measurements based on identical radio hardware. This helps during analysis of the data from the different measurements.
The WLAN module can operate in the 2.4 GHz and the 5 GHz band. The measurements are performed in the 802.11a, 802.11b and 802.11g modes.

The frame logger is a robust version of the FIGO Mobile Node. Due to the limited time available for setting up the tests and performing the research, it was not possible to source 802.11n versions for data logging and throughput tests. The frame logging will include some overhead frames for 802.11n, but not the 802.11n data frames.
In the throughput tests, the results are also valid for 802.11n connections: if there is congestion, this has the same impact on 802.11a/g as on 802.11n.
It was decided not to measure 802.11ac usage, but to scan for APs (802.11ac is backwards compatible with 802.11n) and to measure the overall Radio Frequency use of the 5 GHz band.

For measuring Radio Frequency signal levels, Wi-Spy was used. This tool is developed by Metageek (http://www.metageek.net/products/wi-spy/) and it is a compact USB device, which can track all radio activity from WiFi, cordless devices, microwave ovens, Zigbee, Bluetooth or many other devices. It can also graphically represent the results. This device was used for both the 2.4 GHz and 5 GHz bands.

Figure 2.8 Wi-Spy USB Device and laptop with with Wi-Spy

Also a standard laptop with 802.11a/b/g/n capabilities was used for the throughput measurements, Access Point scan and logging of all results.

2.3.2 Software

On the FIGO Mobile Nodes and laptops measurement software is installed, which are run by scripts. The scripts make sure that the radios are in the right configuration and also sample the radio conditions.
The software is setup in a specific way, to make sure that all measurements are performed in an identical manner.

For measuring available bandwidth and data throughput, iperf was used (https://iperf.fr/). This is an opensource measurement tool. Iperf is a commonly used network testing tool that can create Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) data streams and measure the throughput of a network. It is often used for measuring wired and wireless speeds, and runs on many different platforms. Here iperf was setup to run for a fixed amount of time using TCP traffic, and to measure the amount of data that could be transmitted.

2.4 Locations

According to the research assignment, the following types of areas are relevant:

1. Public Areas in City Centers
2. Business Parks with groups of companies
3. Residential Areas with high rises / flats / apartments
4. Residential Areas with houses in a row / semi-detached

Per area type around 5 to 10 locations are defined, which are carefully chosen as typical examples. Google Streetview was used to aid the selection.
The following types have been determined:

1. Public Areas:
   1a: Shopping Area
   1b: Shopping Mall
   1c: City Center
2. Business Parks:
   2a: Business Park
   2b: Business Parks (indoor)
3. Residential Areas, high rises
   3a: Residential Area, high rise (>10 stories)
4. Residential Areas, houses
   4a, Residential Area, houses in a row
   4b, Residential Area, semi-detached

The additional types were defined to create a results with higher resolution. For example, in residential areas with houses, large differences were expected between locations with houses in a row or semi-detached houses.

The following locations have been selected:

Enschede:
Location 1. 1a, Shopping Area: Kalanderstraat/De Heurne, Stadsgravenstraat
Location 2. 1b, Shopping Mall: De Klanderij
Location 3. 1c, City Center: Oude markt
Location 4. 2a, Business Park: Institutenweg/Marssteden
Location 5. 2b, Business Parks (indoor): Hengelosestraat
Location 6. 3a, Residential Area, high rise (>10 stories): Boulevard 1945
Location 7. 4a, Residential Area, houses in a row: Munsterstraat, Ruwerstraat
Location 8. 4b, Residential Area, semi-detached: Stroinkslanden

Almelo:
Location 9. 4a, Residential Area, houses in a row: Noorderstraat, Asterstraat

Amersfoort:
Location 10. 1a, Shopping Area: Langestraat, Kommestraat
Location 11. 1c, City Center: Achter het oude stadhuis
Location 12. 4a, Residential Area, houses in a row: Celzusterenstraat, Kruiskamp

Arnhem
Location 13. 1a, Shopping Area: Rijnstraat/Vijzelstraat, Bakkerstraat
Location 14. 1b, Shopping Mall: Winkelpassage Het Hemelrijk
Location 15. 1c, City Center: Jansplein, Rijnkade
Location 16. 2a, Business Park: Driepoortenweg
Location 17. 2b, Business Park (indoor): PEJA (Broekstraat 32, Arnhem)
Location 18. 3a, Residential Area, high rises (>10 stories): Driemondplein, Shipholplein, Gorinchemstraat
Location 19. 4a, Residential Area, houses in a row: Agnietenstraat, Pijlkruidstraat
Location 20. 4b, Residential Area, semi-detached: Limburgsingel, Obrechtstraat

Gouda
Location 21. 4a, Residential Area, houses in a row: Mosstraat, Thorbeckelaan

Rotterdam
Location 22. 1a, Shopping Area: Hoogstraat, Witte de Withstraat
Location 23. 1b, Shopping Mall: Winkelcentrum Zuidplein (Zuidplein Hoog 420)
Location 24. 1c, City Center: Spaans Kade, De Meent
Location 25. 2a, Business Park: Bulgersteyn, Blaak/Wijnstraat, bedrijventerrein Noord-West
Location 26. 2b, Business Park (indoor): ECO (Rockanjestraat 13). Cool (Eendrachtsstraat 150)
Location 27. 3a, Residential Area, high rises (>10 stories): 's-Lands Werf, Strevelsweg
Location 28. 4a, Residential Area, houses in a row: Groenezoom, Gerard Scholtenstraat, Opzoomerstraat

Borculo
Location 29. 4b, Residential Area, semi-detached: Kerkstraat

Enschede
Location 30. 2a, Business Park

Almelo
Location 31. 2a, Business Park: Planthofsweg, Edisonstraat, Voltastraat
Location 32. 4b, Residential Area, semi-detached: De bonte specht, de emoe, de condor

Vianen
Location 33. 2b, Business Park (indoor): Lange Dreef, Vianen
Location 34. 2a, Business Park: Lange Dreef, Vianen

On each location measurements are performed on RF, APs, Frame Types and throughput results. Each set of measurements takes around 15 – 20 minutes. Then the tester changes the position by at least 100m and the measurements are repeated. This is done 5 – 10 times. The aim is to measure between 150 and 200 unique locations

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 Centers – during shopping hours including evenings
- Business Parks with groups of companies – during office hours
- Residential Areas (all types) – at the beginning of the evening

2.5 Spectrum Occupancy & Throughput Qualification

An important research question was how to determine spectrum occupancy. Counting the number of APs in a certain location provides some information, but congestion can also happen when there are only 1 or 2 APs found. Many discussions have taken place and several reports have been written on the subject. OFCOM has published a report in June 2013 with a good discussion on spectrum occupancy. On page 25 of the OFCOM report [ref 6], a grade for spectrum occupancy is given based on WiSpy measurement. If the RF signal is present above -86 dBm for more than 20% of the time during busiest hours, the occupancy category is rated as high (see Table 2.5).

Mean occupancy in busiest hour	Occupancy category
Above 20%	High
5% to 20%	Moderate
Below 5%	Low
Below 1%	None

Table 2.5 WiFi Occupancy category according to OFCOM [ref 6]

But spectrum occupancy of 20% does not always mean that there is congestion. The assignment of this research project intended to find out if congestion is taking place. That is the reason that a data throughput test was used. If additional throughput was not possible on the measurement locations, this would also not be possible for other users on those locations.

Because WiFi has a simple scheduling mechanism and the medium is shared between different networks and households, access to the channel will only work effectively until a certain level. Based on practical experience of areas with multiple users, when the spectrum is occupied at 40 – 50%, congestion is already happening. When frames cannot be transmitted at the first instance but have to wait until there is spectrum available, the Round Trip Time is increasing. This is also presented in the next chapter.

The throughput tests are used to determine the available data speed. The maximum data speed with the test setup was 21 Mbit/s, because 802.11a/g was used for these tests. The speeds for 802.11n are higher than the measured speeds.
When the spectrum occupancy is moderate, it is still possible to transmit reasonable amounts of data using 802.11n or 802.11g. For most user applications (especially on mobile devices), data rates above 6 Mbit/s provide satisfactory experiences. However, this limit is arbitrary and increasing over time with new and better applications demanding higher data speeds and lower Round Trip Times (especially for games).
Based on the maximum speed of 21 Mbit/s in the test setup, the achieved data speeds are related to spectrum occupancy. The following qualifications are used:

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, fiber)

Table 2.6 Data Speed & Occupancy Qualification

When the data speed is still good (6 – 12 Mbit/s), there are already some collisions. But when the WiFi speed drops to 3 – 6 Mbit/s, there is definitely some first signs of congestion. Also Round Trip Times increases significantly.
At a measured data speed of 0 – 3 Mbit/s, the WiFi band is severely congested.

3 RESULTS AND ANALYSIS

3.1 Introduction

This chapter discusses and analyzes the measurements results, based on the research questions presented in chapter 2. This chapter is divided in three main sections. First a summary of all results is given, after which the results are analyzed per scenario, and finally a number of other observations not specific for a scenario are presented.

The measurements have been performed over several weeks during November and December 2014. An overview of the test locations is provided in the figure below.

Figure 3.1 Overview Test Locations

On each location measurements have been performed on RF, APs, and data throughput results. The outdoor measurements also logged the Frame Types . The raw measurement data is stored in logging files. The relevant data is retrieved and number of SSIDs, RSSI, frame types, etc. is determined. The information is then summarized and translated into graphs.
An overview of the measurement locations and number of measurements is given in Table 3.1.

City\Type	1a	1b	1c	2a	2b	3a	4a	4b
Enschede (Ziggo)	4 (mob)	4 (mob)		5 (car) 5 (car)		5 (car)	8 (car)	8 (car)
Almelo (Ziggo)				10 (car)			10 (car)	10 (car)
Amersfoort (Ziggo)	4 (mob)						10 (car)	
Arnhem (UPC)	1 (mob)	3 (mob)		10 (car)	4 (mob)	4 (car)	10 (car)	7 (car)
Gouda (Caiway)							8 (car)	
Rotterdam (UPC)	5 (mob)	5 (mob)	1 (mob)	10 (car)		5 (car)	10 (car)	
Borculo (CaiWay)								10 (car)
Vianen (Ziggo)				3 (car)	4 (mob)			
subtotals	14	12	1	43	8	14	56	35
	Total number of measurement locations							183

Table 3.1 Measurement locations

3.2 Overall Observations

In paragraph 2.5 a qualification is presented for measuring WiFi throughput. Figure 3.2 and Figure 3.3 show the summarized classification of throughput measurements of the 2.4 GHz and 5 GHz band. The overall observation is that on the 2.4 GHz there is a significant number of measurements where problems with WiFi are observed, while on the 5 GHz band, no problems have been encountered. This is based on the throughput results and occupancy qualification of paragraph 2.5. On the 5 GHz band, all performance measurements show good or very good throughput, while on the 2.4 GHz band, in 19.5% of the measurements the throughput was considered bad or very bad. Other measurements confirm this general view of the status of WiFi in both frequency bands.

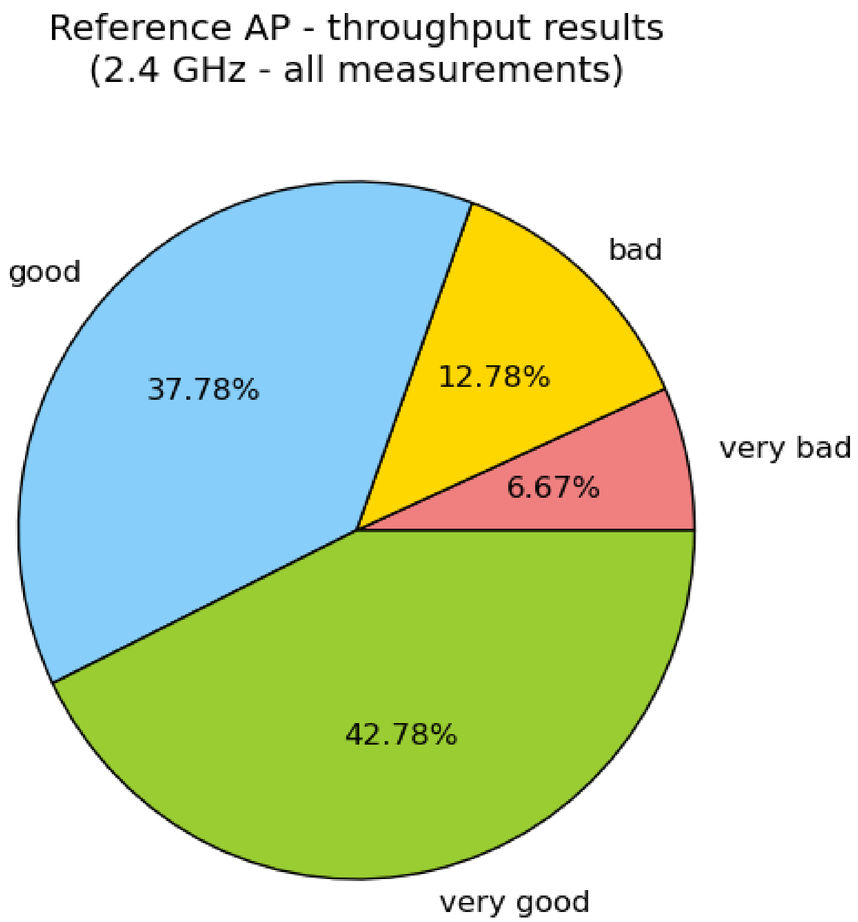

Figure 3.2: Classification of throughput for all measurements on 2.4 GHz

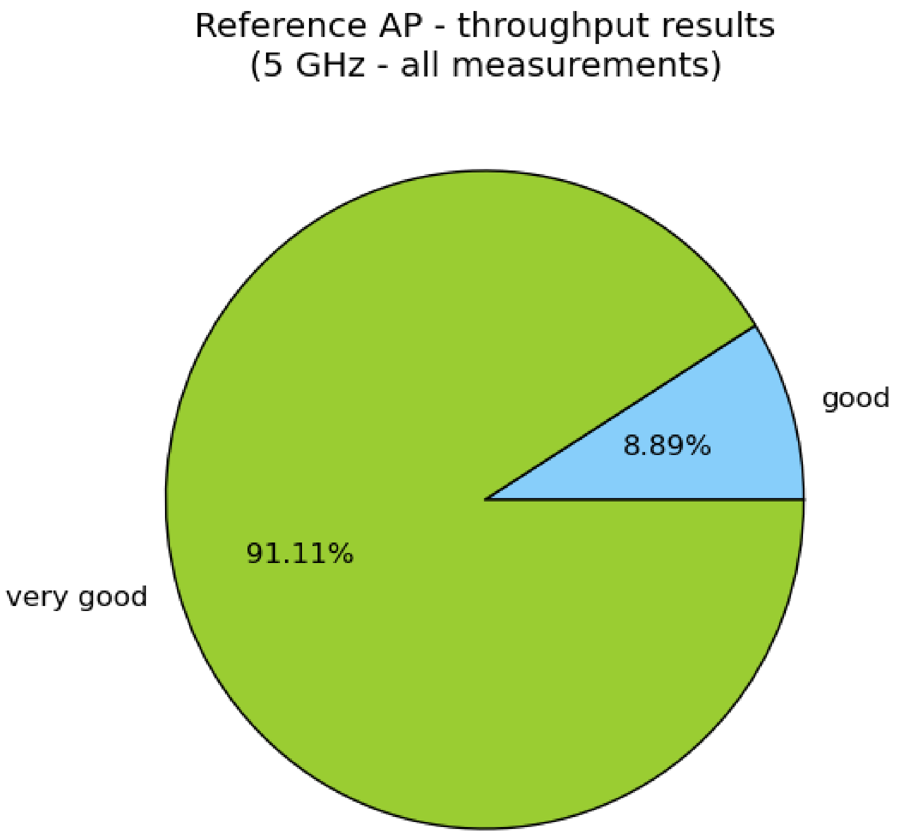

Figure 3.3: Classification of throughput for all measurements on 5 GHz

Besides the two frequency bands, multiple cross-sections of the data can be made. The following sections separately discuss the scenarios defined in the original assignment. Results for these four scenarios are summarized in Figure 3.4 and Figure 3.5, for 2.4 GHz and 5 GHz respectively. These graphs show, for each area type, the average measured performance per measurement (throughput and round trip time), the average number of detected Access Points per measurement, and the average number of detected devices (unique MAC addresses) per measurement.

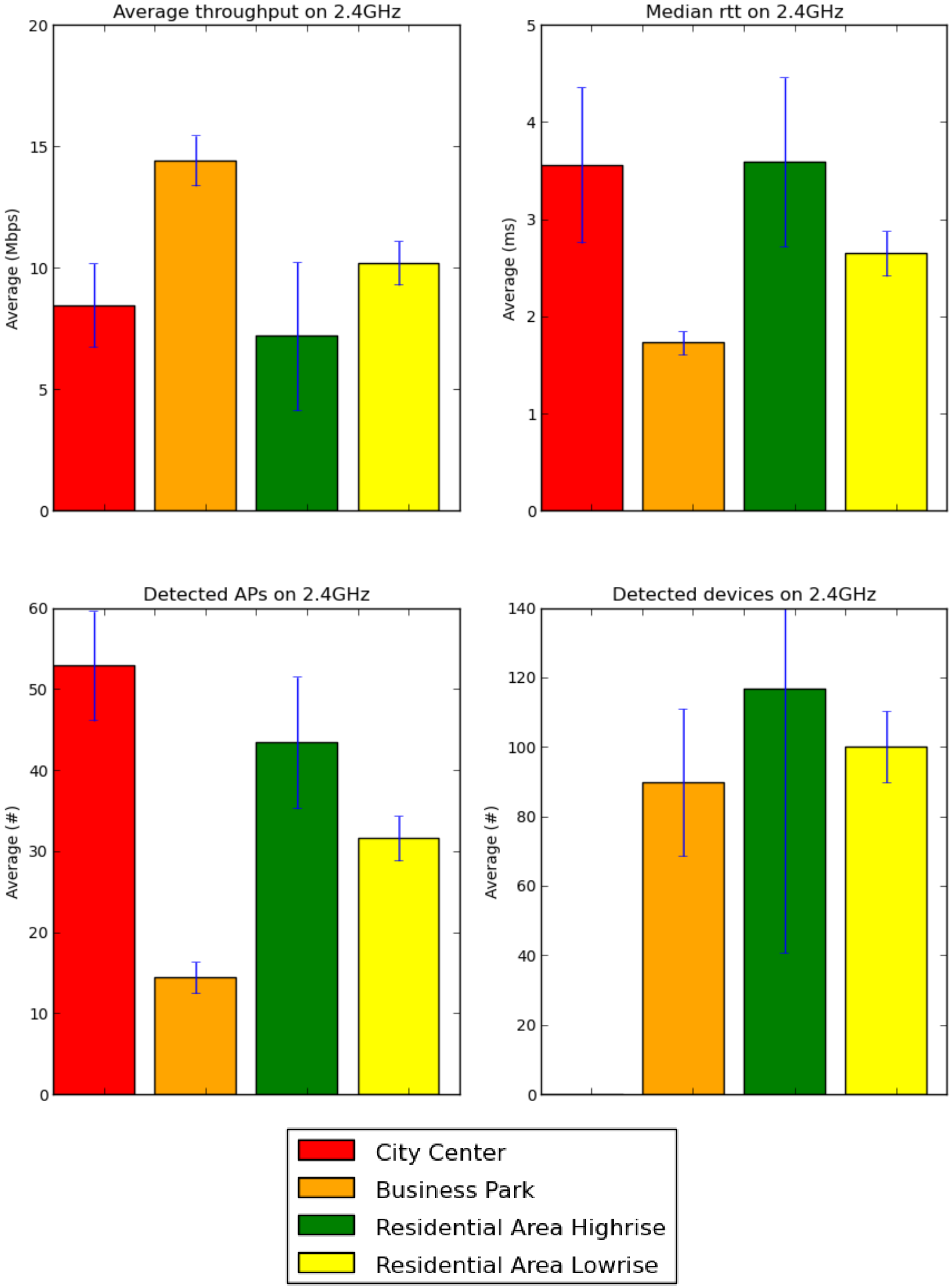

Figure 3.4: Summary of 2.4 GHz results per scenario

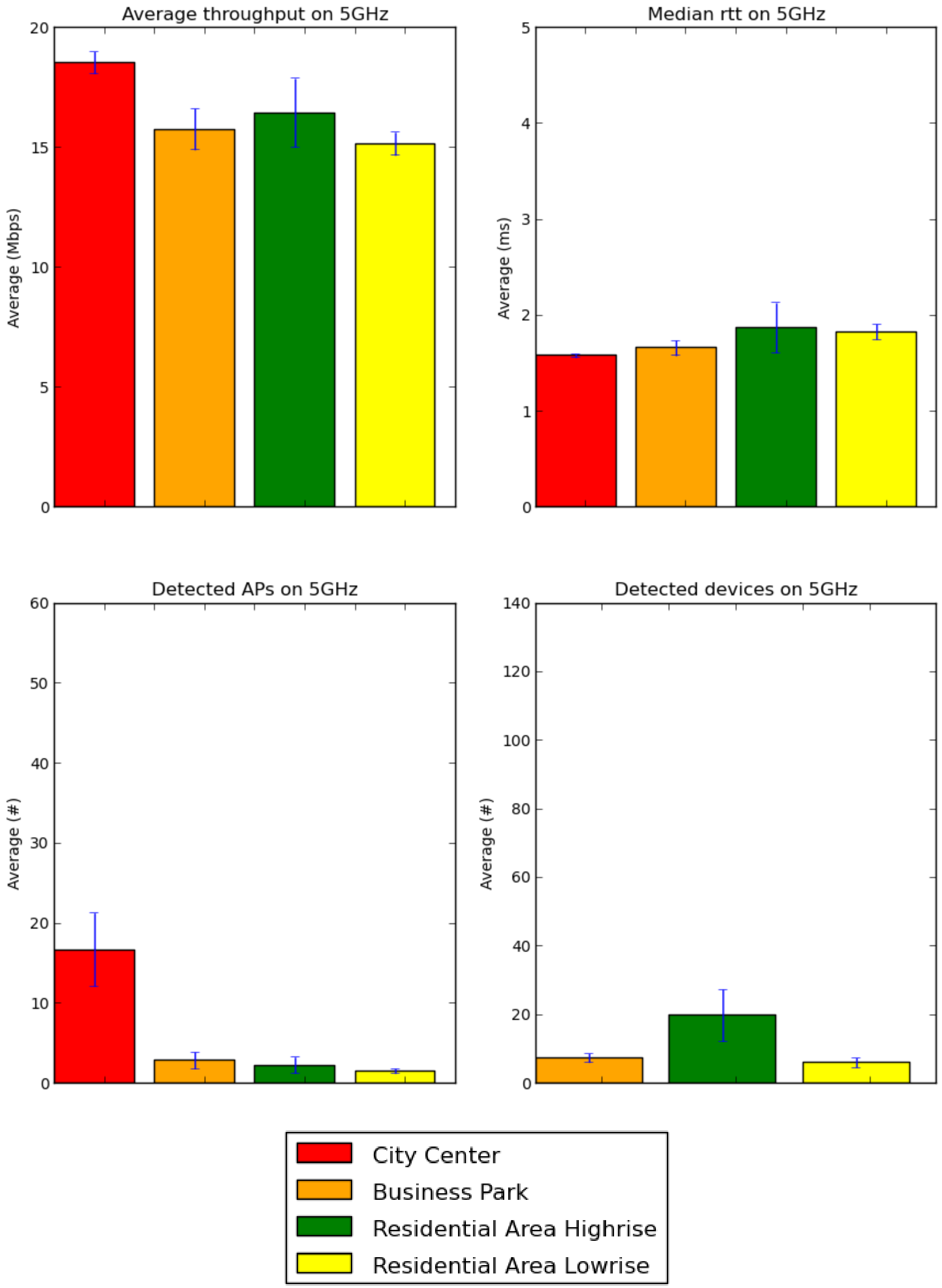

Figure 3.5: Summary of 5 GHz results per scenario

Comparing the two figures confirms the previous observation about the 5 GHz band:

- The performance measurement shows both a very good throughput and round trip time. Note that in City Centers the performance is slightly better, which can be explained by the differences between the mobile and car measurement setups.
- The number of detected Access Points is quite low, which can be explained both by an actual lower number of Access Points, but also by the inherent lower range of 5 GHz networks compared to 2.4 GHz networks. Doubling the radio frequency normally leads to halving the range for a given output power.
- In City Centers, the average number of detected networks is higher, which can partially be explained by the use of the mobile setup (i.e. the measurement is done closer to network), but not completely. A possible cause of the increase in 5 GHz networks could be the congestion on 2.4 GHz in these environments, which can be seen in more detail in the following sections.
- The number of detected devices confirms the previous statements. Note that this measurement was not included in the mobile setup.

Looking at the average results on the 2.4 GHz, also a number of observations can be made, which are discussed in more detail per scenario in the following sections:

- The measurements on Business Parks show good performance and relatively quiet radio environments.
- Both the number of detected Access Points and devices, and the performance measurements indicate that on average the performance degrades significantly. In individual measurements the situation can be much worse.
- The number of detected devices is quite low. This probably relates to the length of the frame sniffing measurement. A longer measurements is expected to increase the number of devices observed. Within the scope of this project a large number of short measurements was preferred, likely resulting in an underestimation of the number of devices present.

3.3 Scenario: City Centers

In city centers, all measurements were performed with the mobile measurement setup. Three additional scenarios were defined: shopping malls (indoor), shopping areas (outdoor) and entertainment areas (bars, restaurants, etc.). Measurements show no significant differences between the first two, while for the third only one measurement was done (e.g. restaurant owners did not permit measurements near their terraces).

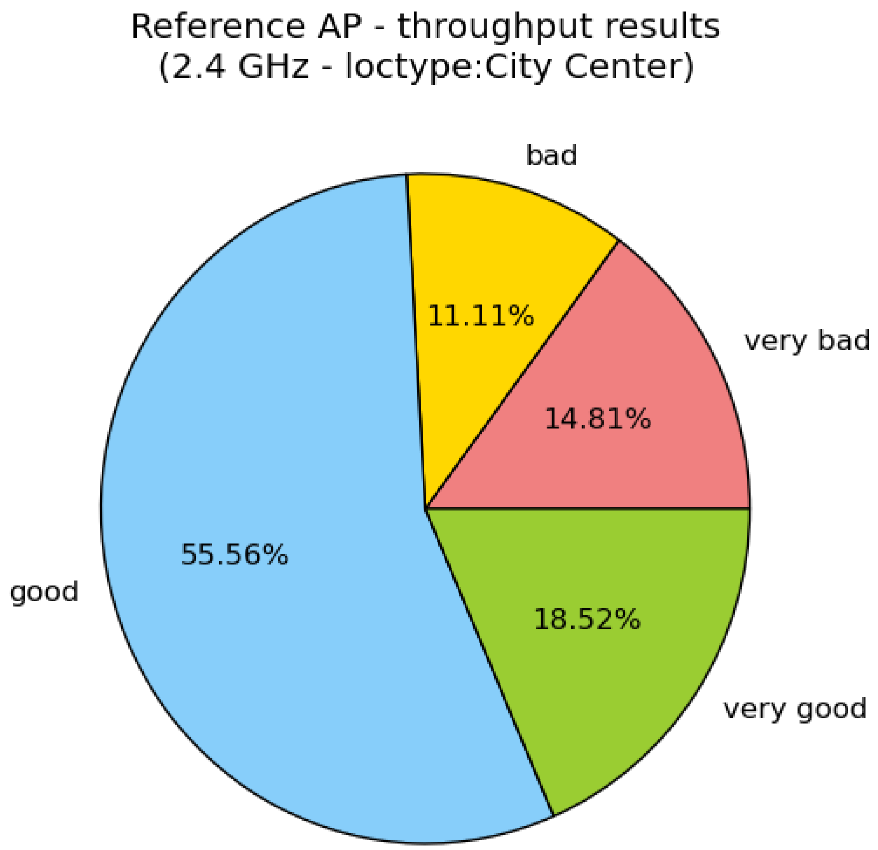

Figure 3.6: Classification of throughput for city center measurements on 2.4 GHz

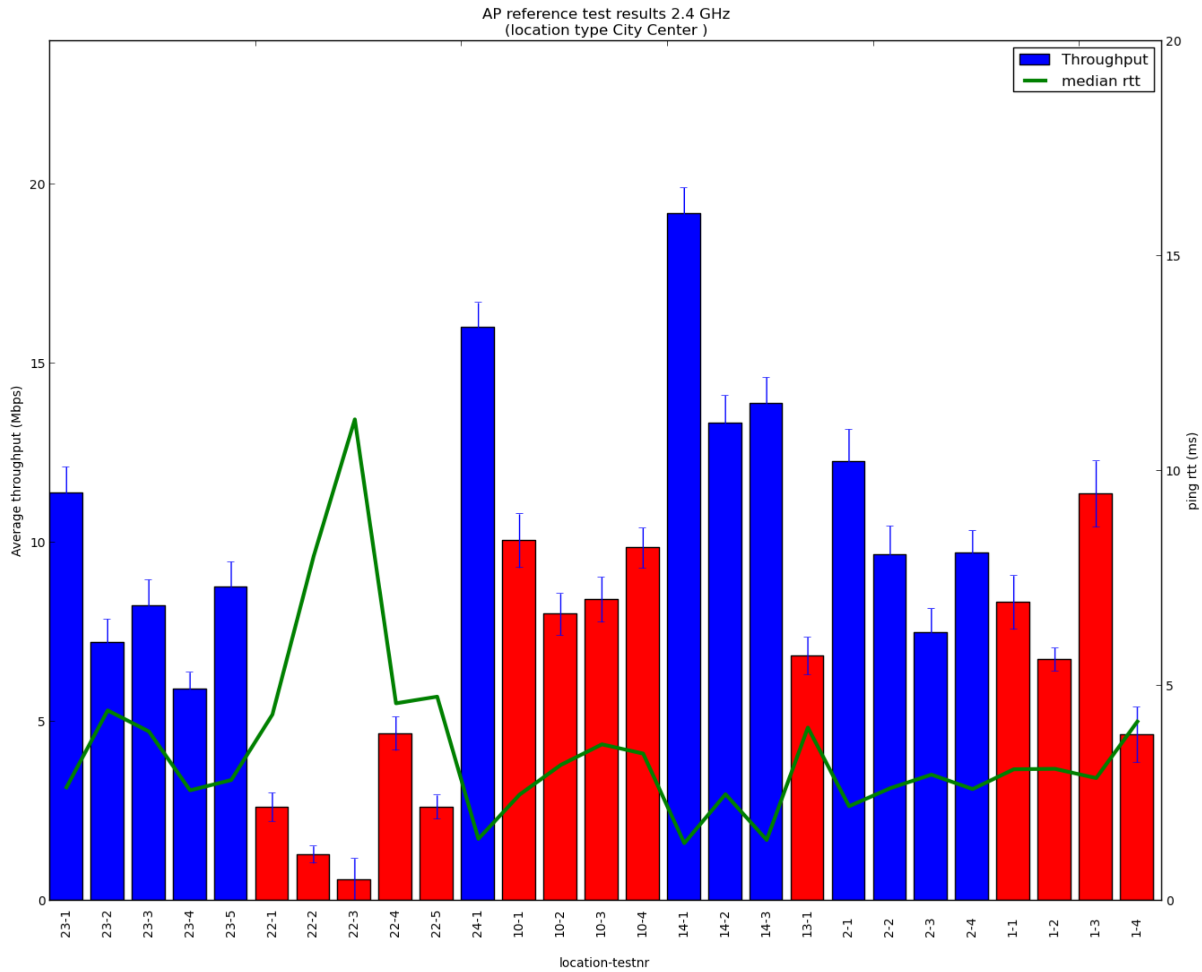

Figure 3.7: 2.4 GHz performance measurement results in city centers

Figure 3.6 shows the average performance in city centers is worse than the overall average (as seen in Figure 3.2). Figure 3.7 confirms this showing the results of the performance measurement (both measured throughput and round trip time) for each measurement location in city centers. Blocks of adjacent bars in the same color correspond to multiple measurement points on a single location. It is clear that most measurements are below the ‘very good’ level; confirming the above average performance degradation in this scenario.

This is confirmed by the WiSpy measurements, which show lots of RF activity across the 2.4 GHz band, see for example Figure 3.8. Also, the number of 5 GHz Access Points is much higher in City Centers. All WiSpy measurements show a scale in dBm.

The 5 GHz band is mostly very quiet. Figure 3.10 shows the WiSpy results on 5 GHz in the Rotterdam City Center, which is one of the few 5 GHz measurements where significant RF activity can be observed. A likely explanation for the increased use of the 5 GHz band is the congestion on

2.4 GHz. However, the performance measurements on the 5 GHz band show no degradation in throughput or round trip time, see Figure 3.11.
In Figure 3.7, the second set of measurements show the situation in Rotterdam (location 22) to be much worse than the average of City Centers. Again, this is confirmed by other measurements, see e.g. the WiSpy results on 2.4 GHz in Figure 3.9 (this location corresponds to the 5 GHz spectrum shown in Figure 3.10). The measurements in Rotterdam suggest that congestion on the 2.4 GHz band causes the performance to drop below minimal requirements for many applications.

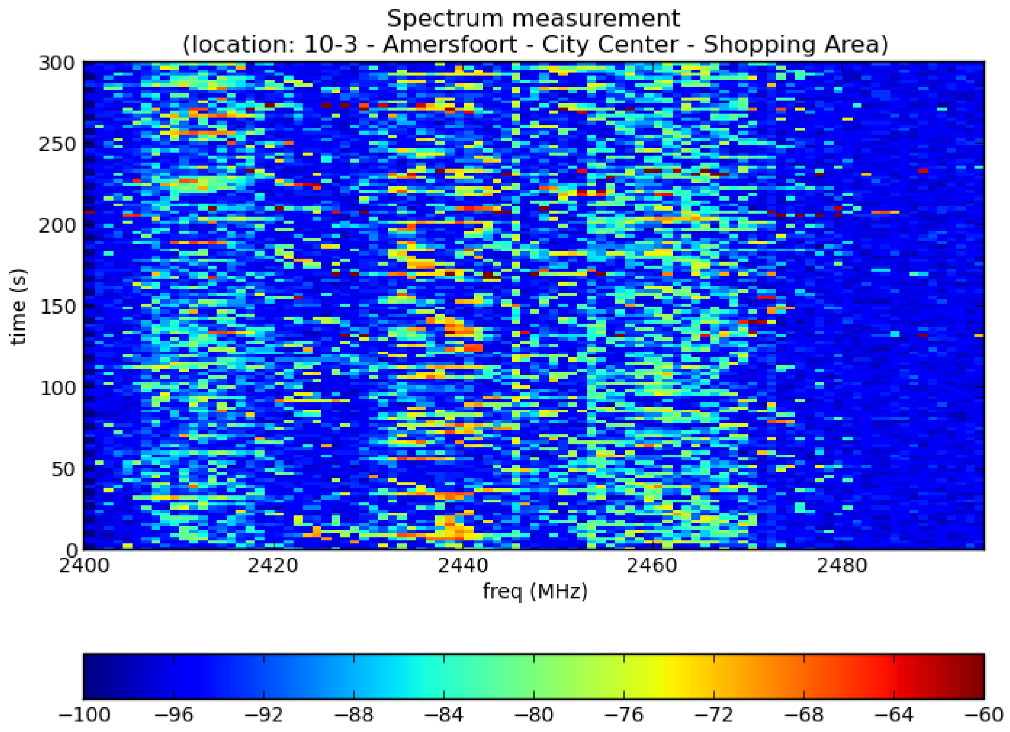

Figure 3.8: WiSpy measurement 2.4 GHz Amersfoort city center (dBm)

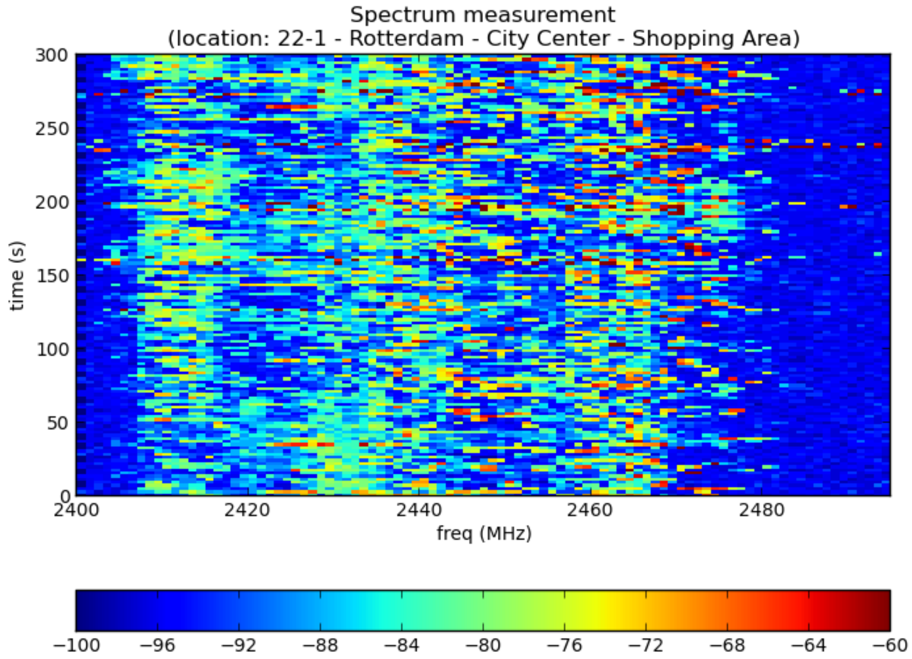

Figure 3.9: WiSpy measurement 2.4 GHz Rotterdam City Center (dBm)

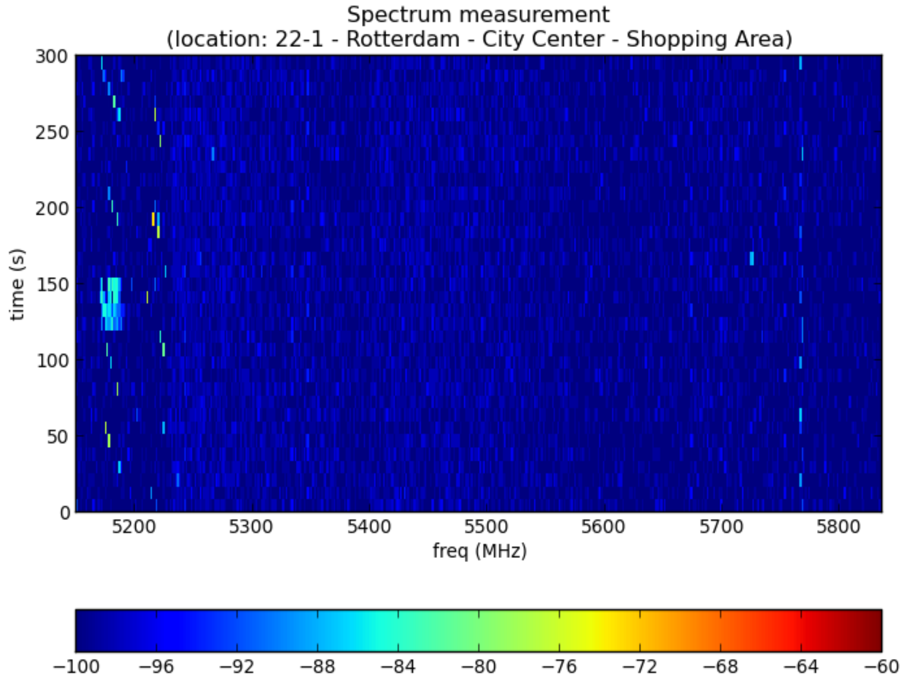

Figure 3.10: WiSpy measurement 5 GHz Rotterdam City Center (dBm)

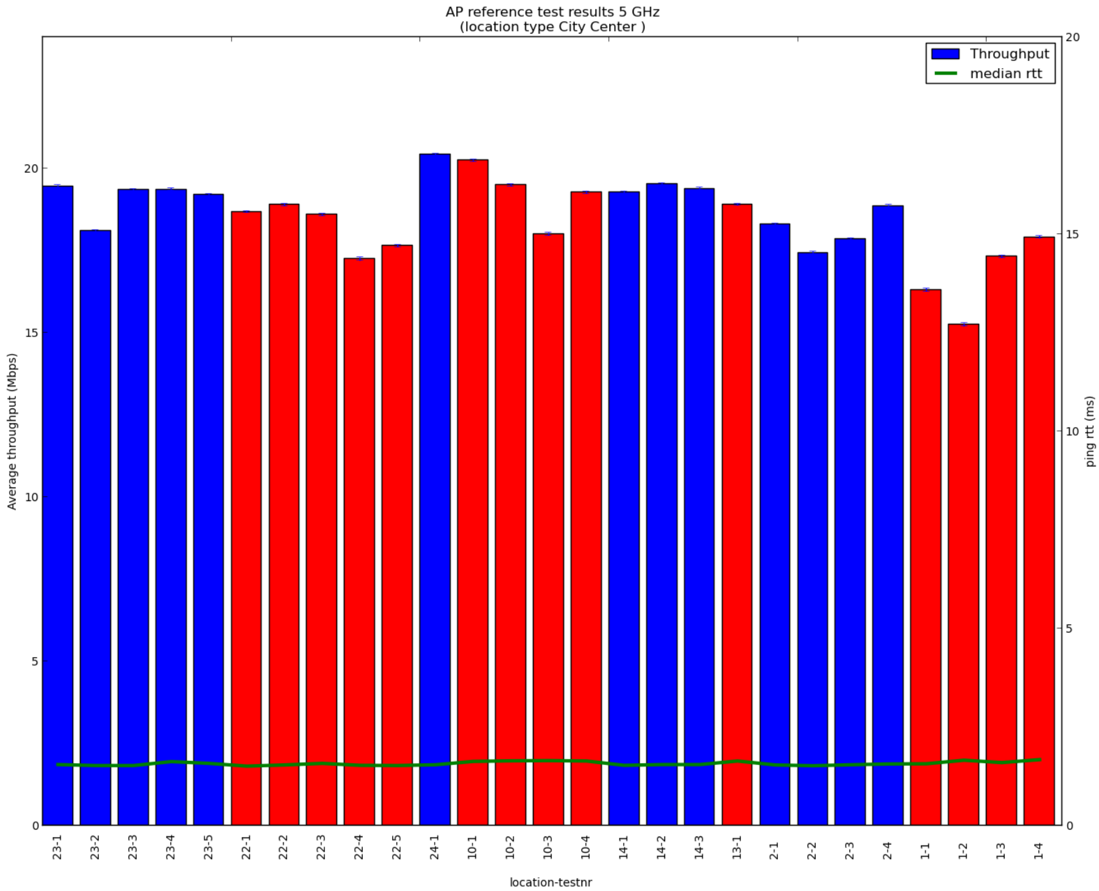

Figure 3.11: 5 GHz performance measurement results in City Centers

3.4 Scenario: Business Parks

On business parks, two types of measurements have been performed, outdoor measurements with the car setup and indoor measurements (locations 17 and 33) with the mobile setup. As already seen in Figure 3, on average the usage of the 2.4 GHz is less compared to residential areas and city centers. This is also reflected in the performance measurements, see Figure 3.12 and Figure 3.13. Both the throughput and the round trip time measurement show mostly good performance. When incidentally a lower performance is observed, in most cases this can be explained by looking at other measurements. For instance on location 16-2, where an average throughput of 6.6Mbps was achieved, the WiSpy measurement (see Figure 3.14) on the same location shows lots of WiFi activity on channel 8, which overlaps with channel 11 on which the performance measurement was done.

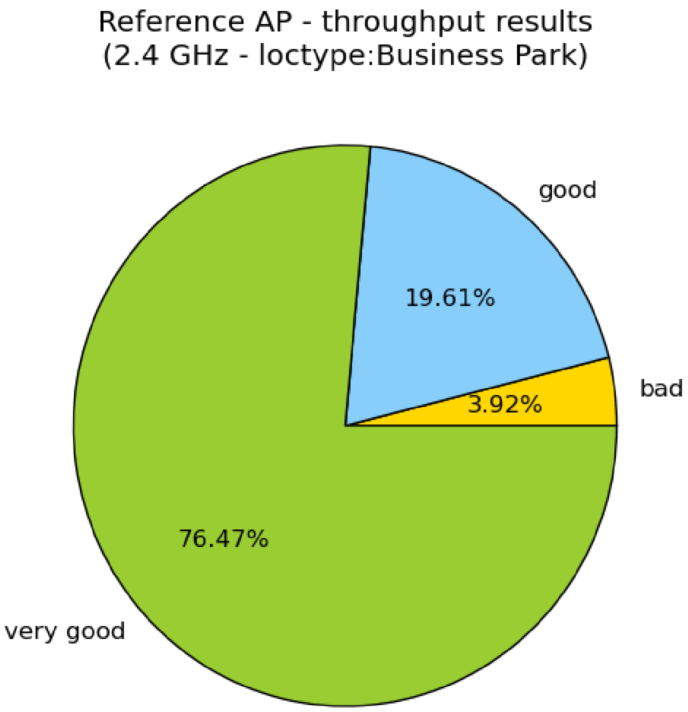

Figure 3.12: Classification of throughput for Business Park measurements on 2.4 GHz

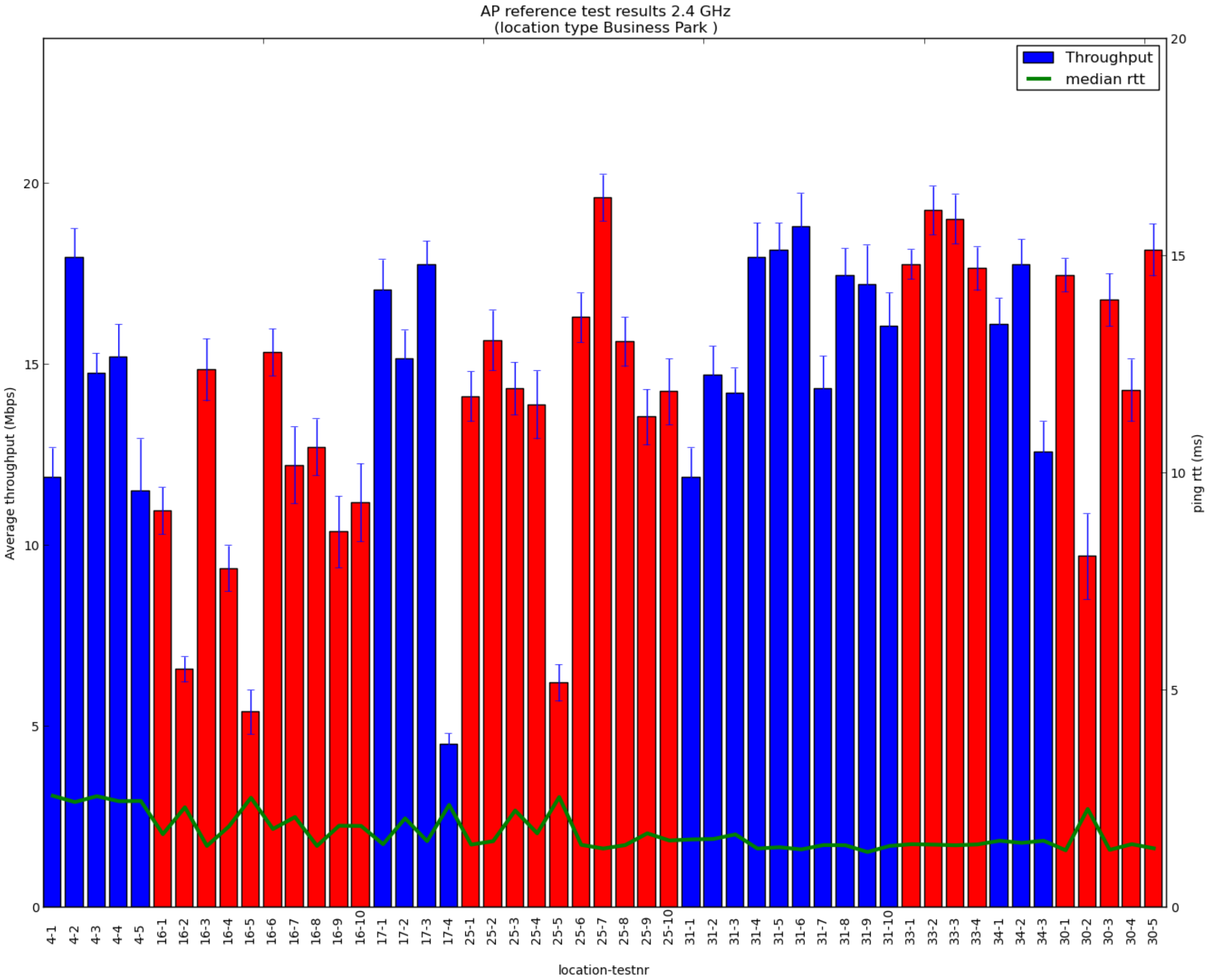

Figure 3.13: 2.4 GHz performance measurement results on Business Parks

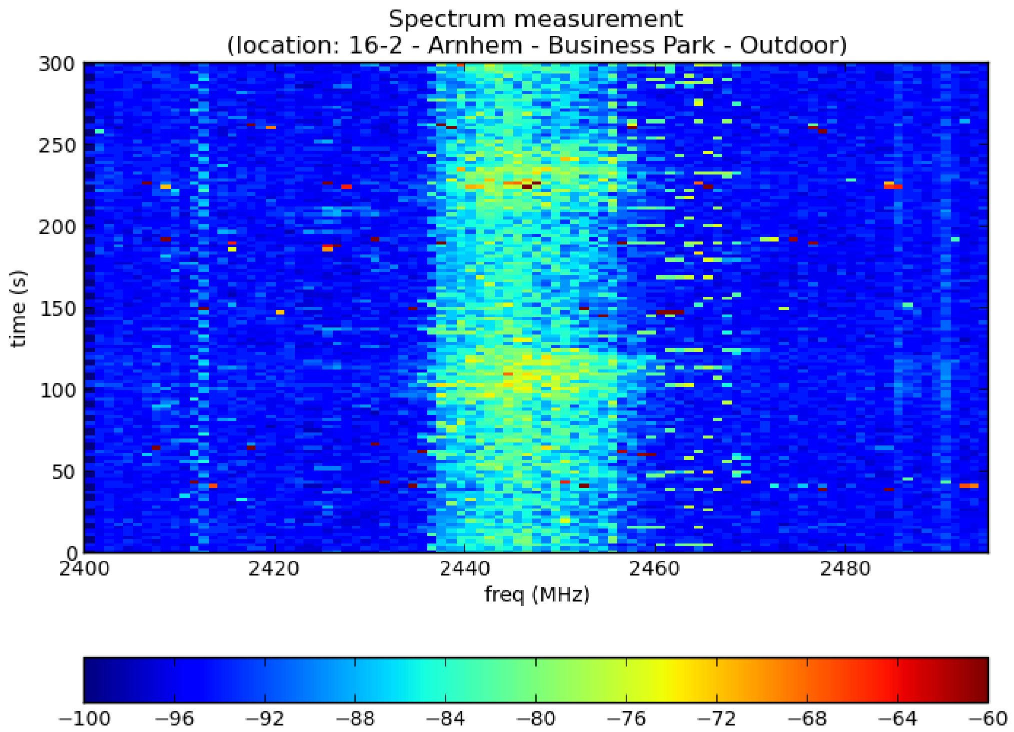

Figure 3.14: WiSpy measurement 2.4 GHz Arnhem Business Park outdoor (dBm)

The measurements on location 33 and 34 were executed indoor and outdoor at the same location. Comparing the indoor and outdoor measurements on 2.4 GHz, WiFi activity can be seen on multiple channels in the indoor results in Figure 3.15, but much less on the outdoor results in Figure 3.16. Of course this can be explained both by a larger distance to the WiFi sources, and attenuation by the walls of the building. The outdoor measurements are indicative for the effect of WiFi on neighboring buildings.
Note that the difference in average performance on these locations can be explained by the difference between the mobile and the car setup.

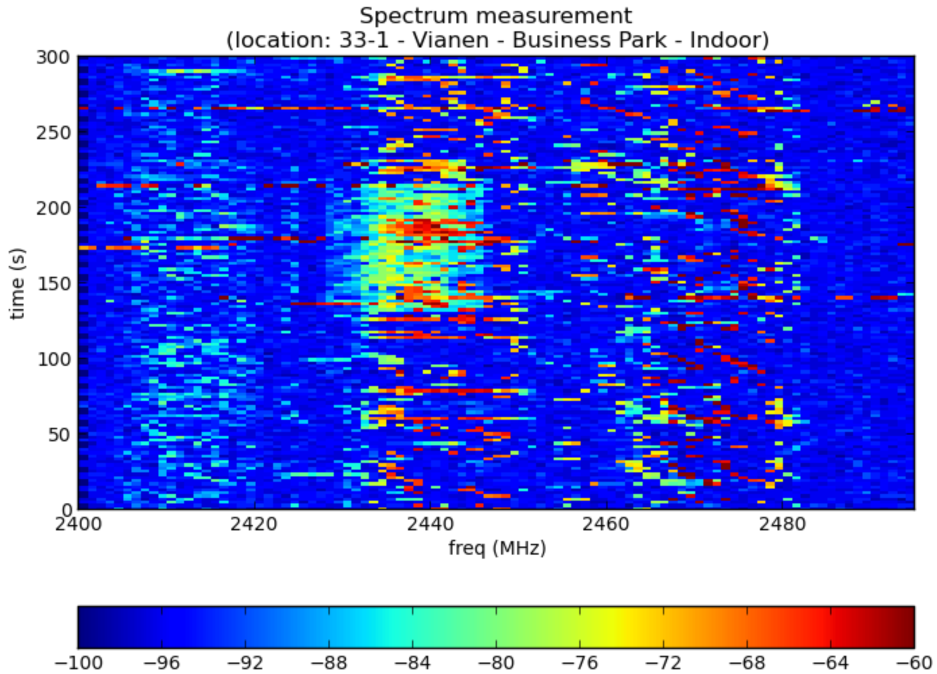

Figure 3.15: WiSpy measurement 2.4 GHz Vianen Business Park indoor (dBm)

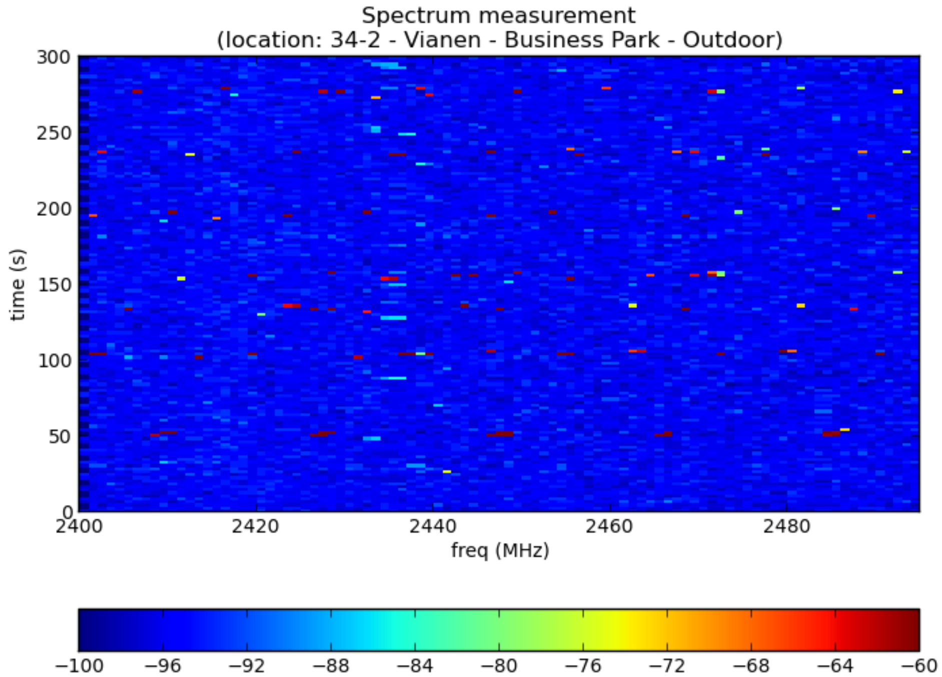

Figure 3.16: WiSpy measurement 2.4 GHz Vianen Business Park outdoor (dBm)

3.5 Scenario: Residential, high rise

The measurements around high rise residential buildings were all done around buildings with at least 10 stories. Because only car measurements have been performed outside the buildings, and the materials used on the front and back of these buildings (e.g. mostly glass, little or no reinforced concrete), it was expected that the car measurements would show a busy WiFi environment in this type of areas. However, the performance measurements (see Figure 3.17 and Figure 3.18) show below average results both for the throughput and round trip time.

It is clear from Figure 3.18 that one of the three locations was very bad in particular. In the other two locations, the performance might be less than expected, but still acceptable. The cause for the bad performance on location 6 is not known, it cannot be explained from the WiSpy measurements at the same location. Looking at Figure 3.19 and Figure 3.20, high RF levels around channel 11 for location 6-4 is shown, but the spectrum on location 6-5 would not suggest any issues. A remark should be made here that the WiSpy measurement is not done during the performance measurement (otherwise the measurements would interfere), and that the WiSpy measurement is done on one location (near our reference Access Point), while our test client for the performance measurement is some distance away. Although this is only 10m, it could be possible that the client has interference, while the Access Point does not.

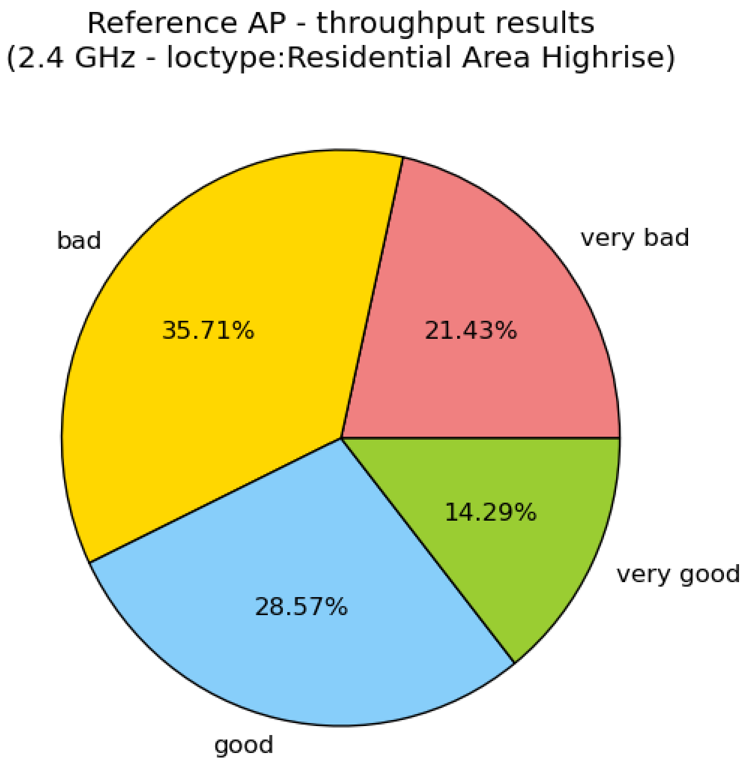

Figure 3.17: Classification of throughput for Residential high rise measurements on 2.4 GHz

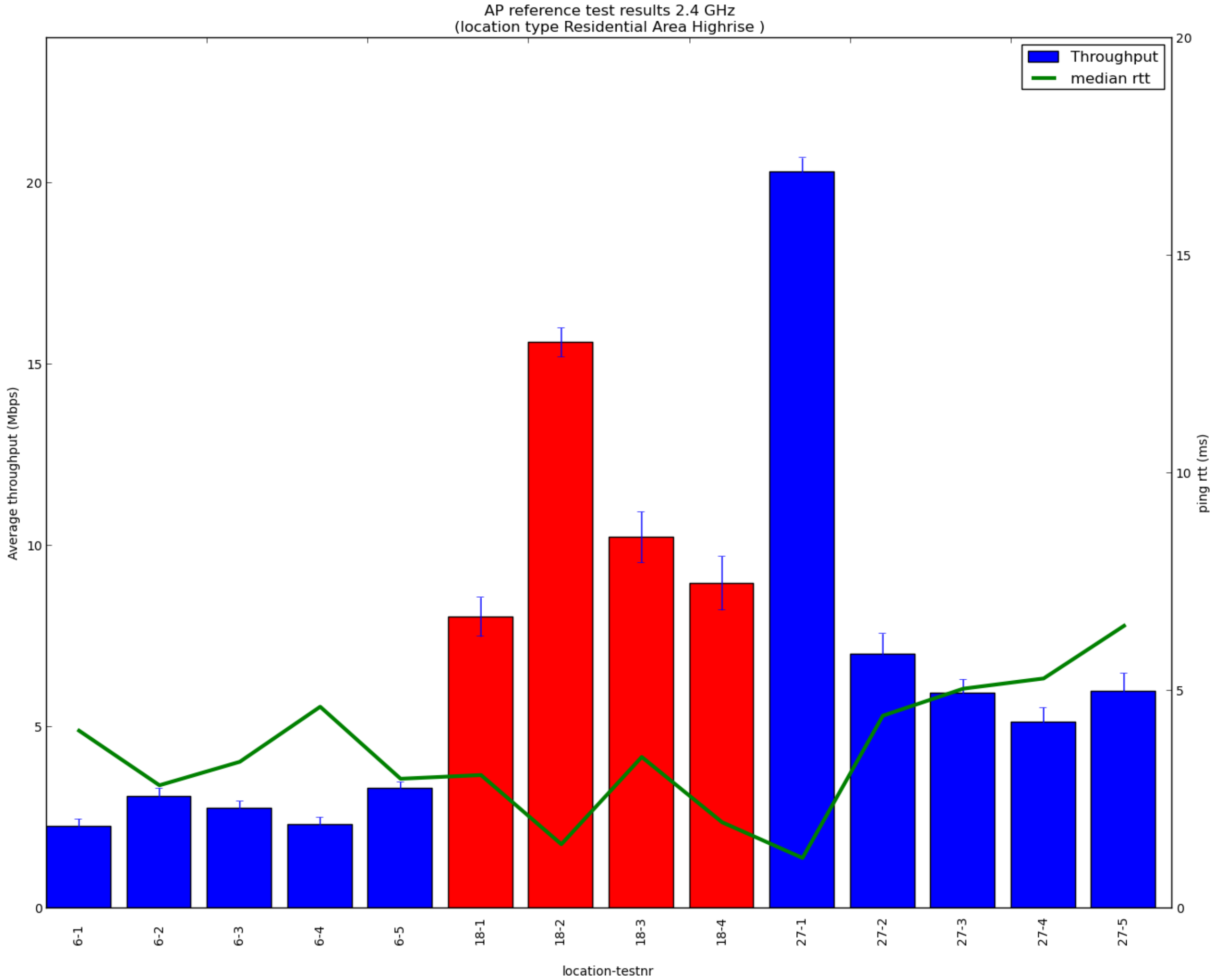

Figure 3.18: 2.4 GHz performance measurement results in Residential high rise areas

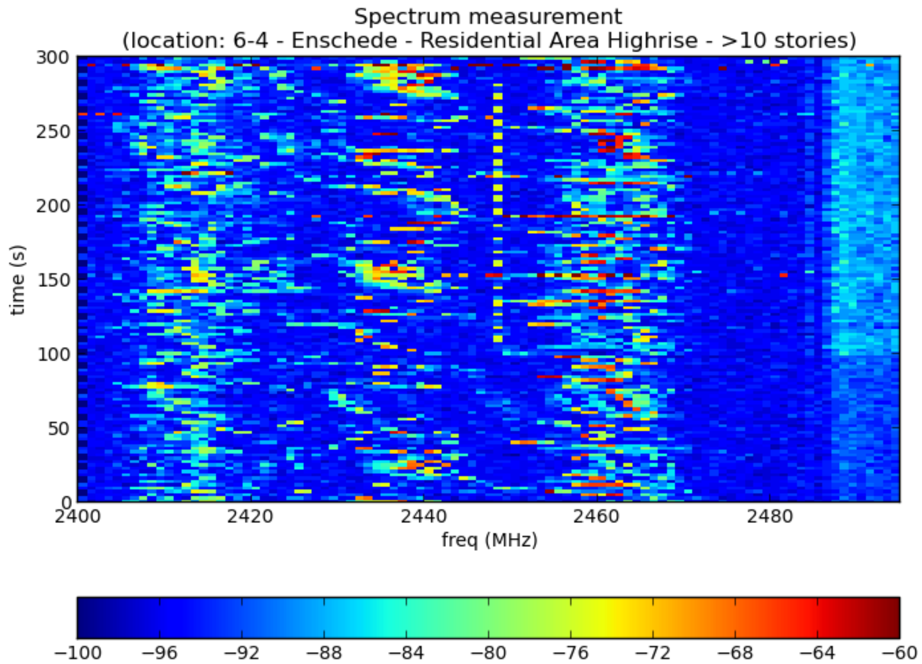

Figure 3.19: WiSpy measurement 2.4 GHz Residential high rise, location 6-4 (dBm)

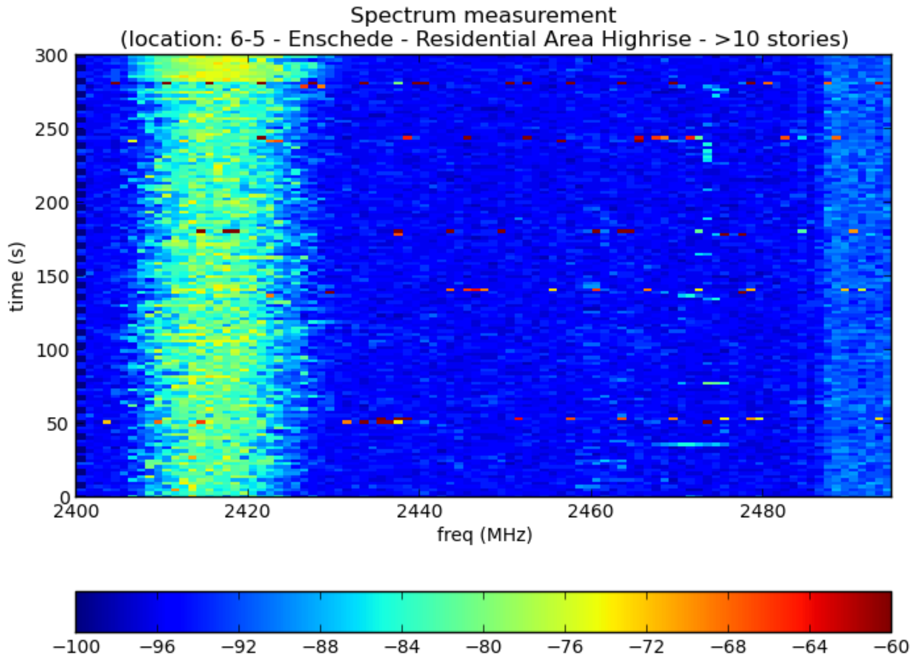

Figure 3.20: WiSpy measurement 2.4 GHz Residential high rise, location 6-5 (dBm)

3.6 Scenario: Residential, low rise

In the low rise residential scenario, a separation has been made between two types of residential low rise area types: houses in a row in older areas with a high density of people (with building construction were one would expect low RF isolation) and semi-detached houses in newer areas (with a lower density of people and higher RF isolation levels).

The performance measurements for the measurements in newer city areas are shown in Figure 3.21 and Figure 3.23, while the results for the older city areas are shown in Figure 3.22 and Figure 3.24. Comparing these two sets of images, confirms the expectation that more problems would be found in areas with (older) houses in a row. The average performance, both when looking at the throughput and the round trip time is much worse in these areas.

But it is also interesting to see that there are two types of deviations to the average performance (which is not limited to this scenario; this is basically seen in all four scenarios).
First, there are individual measurements in which the performance is significantly different from other measurements on the same location. These “incidents” could be explained by the measurement happening at the same time with some specific WiFi activity (e.g. a large file download) on a nearby access point, or other sources of local interference.

Secondly, there are locations where the average performance is significantly different. In this scenario a good example is location 28 in Rotterdam (see Figure 3.24). This difference compared to other locations of the same area type cannot be explained from the measurements.
The WiSpy measurements in this area type typically correspond to the performance measurements. Also, the same variation in good and bad sites can be found. In Figure 3.25, Figure 3.26, and Figure 3.27, three examples are provided showing respectively a relatively unoccupied, a typical, and a spectrum with high RF levels in the entire 2.4 GHz band.

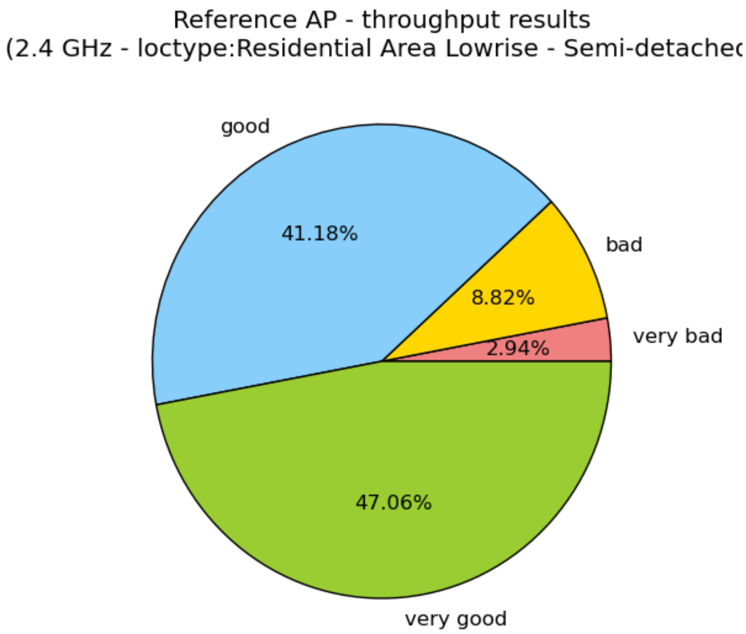

Figure 3.21: Classification of throughput for Residential low rise, semi-detached houses measurements on 2.4 GHz

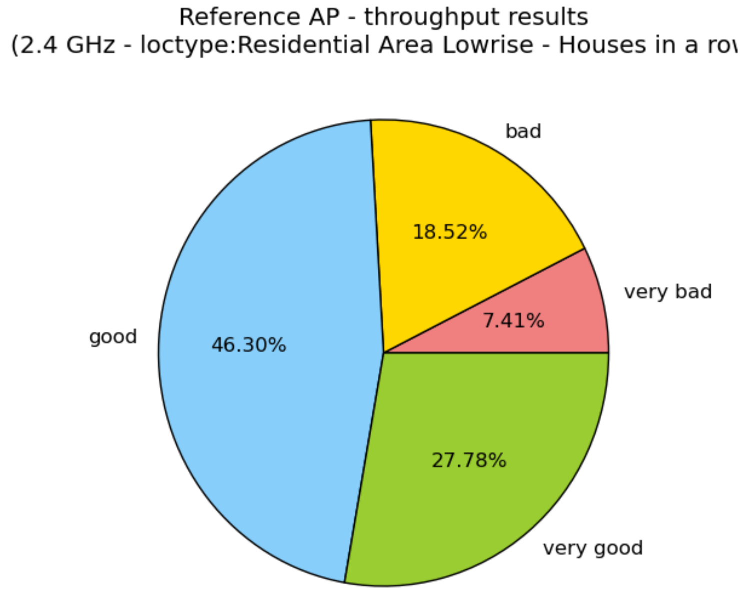

Figure 3.22: Classification of throughput for Residential low rise, houses in a row measurements on 2.4 GHz

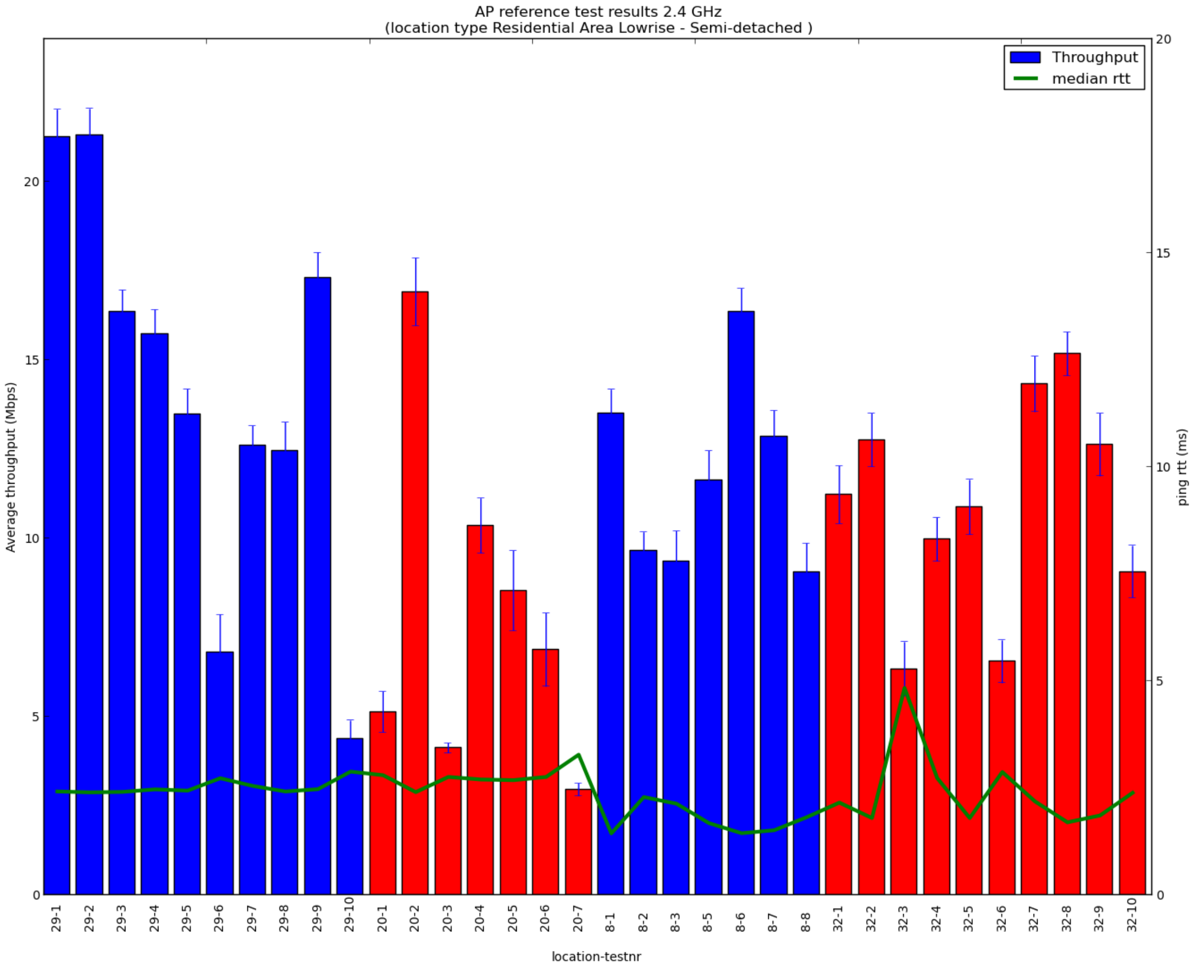

Figure 3.23: 2.4 GHz performance measurement results in Residential low rise areas, semi-detached houses

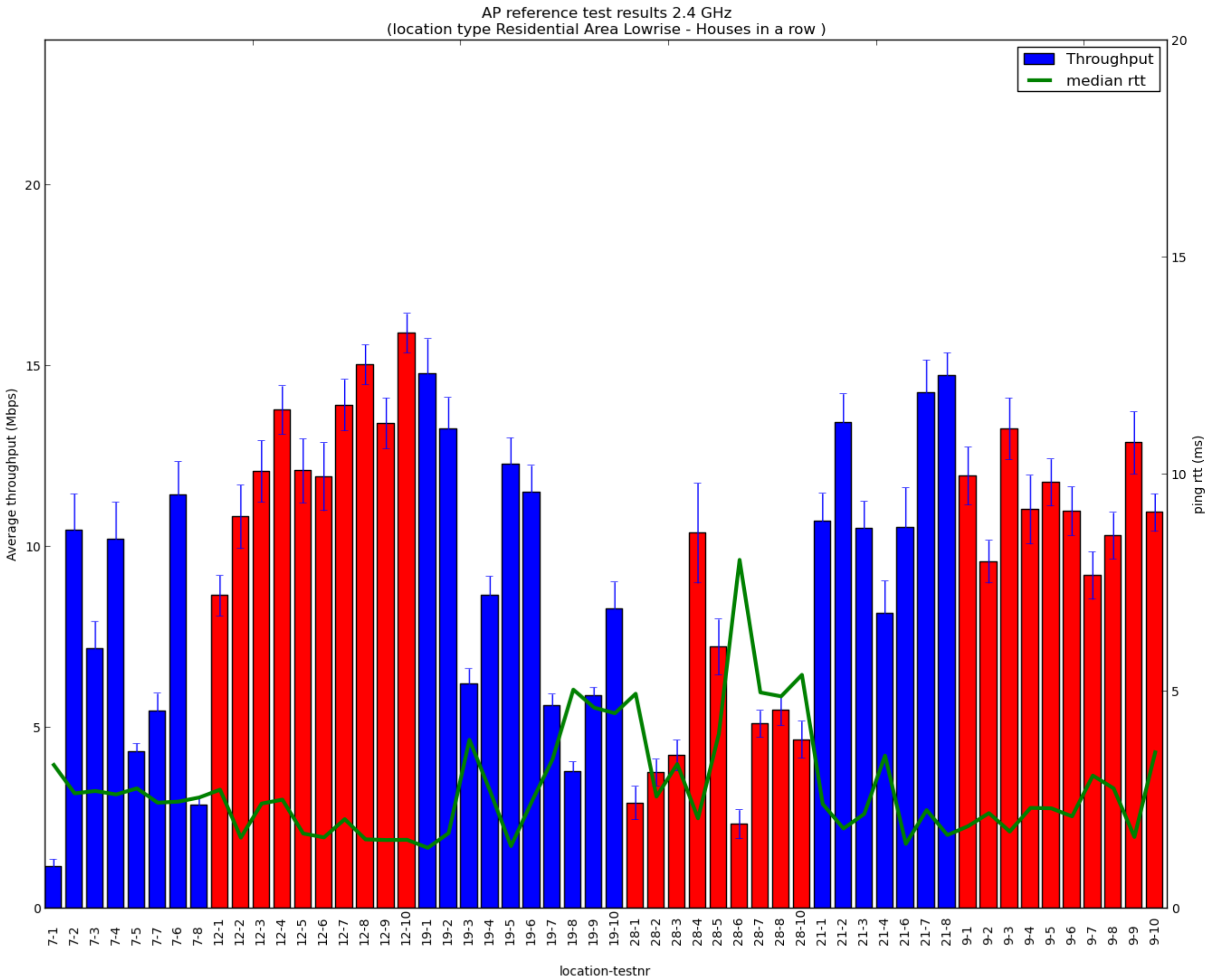

Figure 3.24: 2.4 GHz performance measurement results in Residential low rise areas, houses in a row

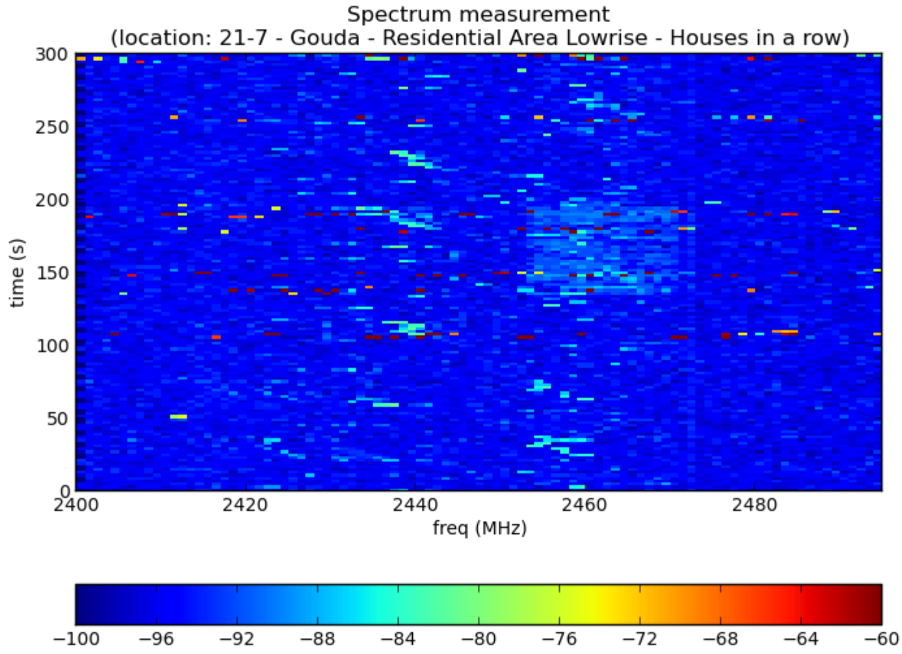

Figure 3.25: WiSpy measurement 2.4 GHz Residential low rise, location 21-7 (dBm)

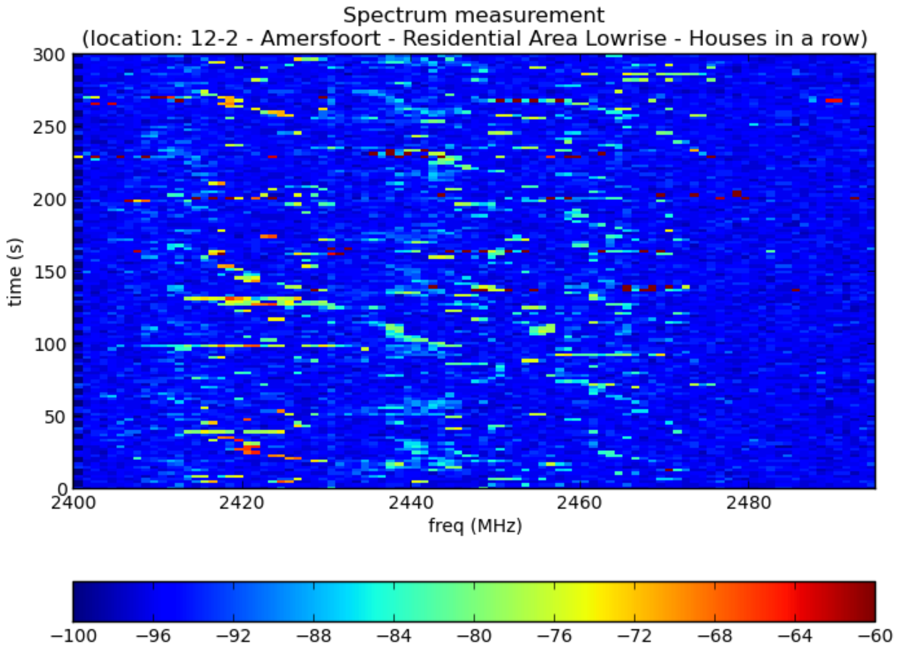

Figure 3.26: WiSpy measurement 2.4 GHz Residential low rise, location 12-2 (dBm)

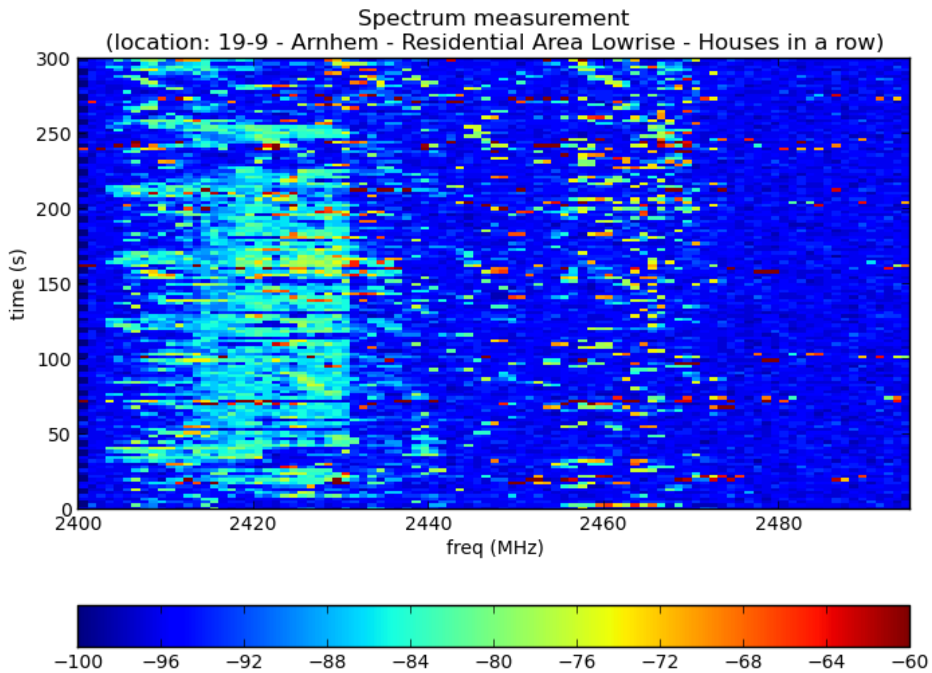

Figure 3.27: WiSpy measurement 2.4 GHz Residential low rise, location 19-9 (dBm)

3.7 Non-WiFi Interference

Non-WiFi interference can be observed in the WiSpy measurements. In the measurements no obvious effect of the interference on WiFi performance was seen. Experience has shown that various type of interference can cause issues with WiFi networks (e.g. Bluetooth devices, wireless video transmitters, car alarms, etc.). In some WiSpy measurements the interference is such that problems can be expected on some channels. However, the general picture is that non-WiFi signals are not a major cause for issues with WiFi. If there are strong interference sources, they are limited to part of the 2.4 GHz band.

An example of problematic interference is shown in Figure 3.28, the performance of channels around 2450 MHz (channels 6 – 9) is definitely influenced by this.

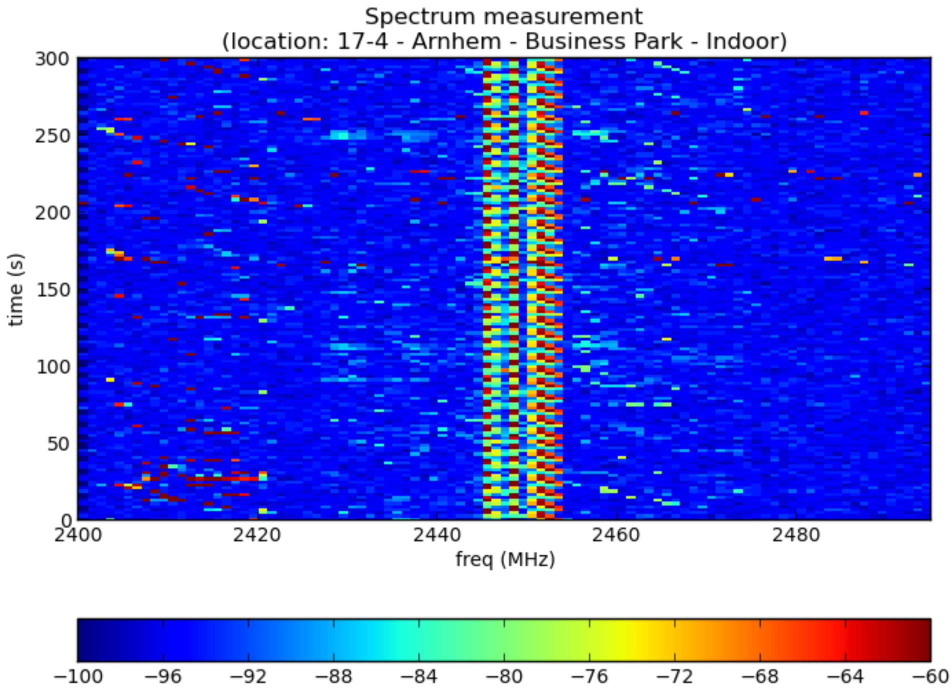

Figure 3.28: WiSpy measurement 2.4 GHz Business Park indoor, location 17-4 (dBm)

Similar interference patterns are seen in Figure 3.29, where also horizontal non-WiFi patterns can be found. It is typical to see that the intermittent narrowband signal seen in Figure 3.29, is not present in the previous measurement on the same location in Figure 3.30. However, each next measurement is done at least 100m away.

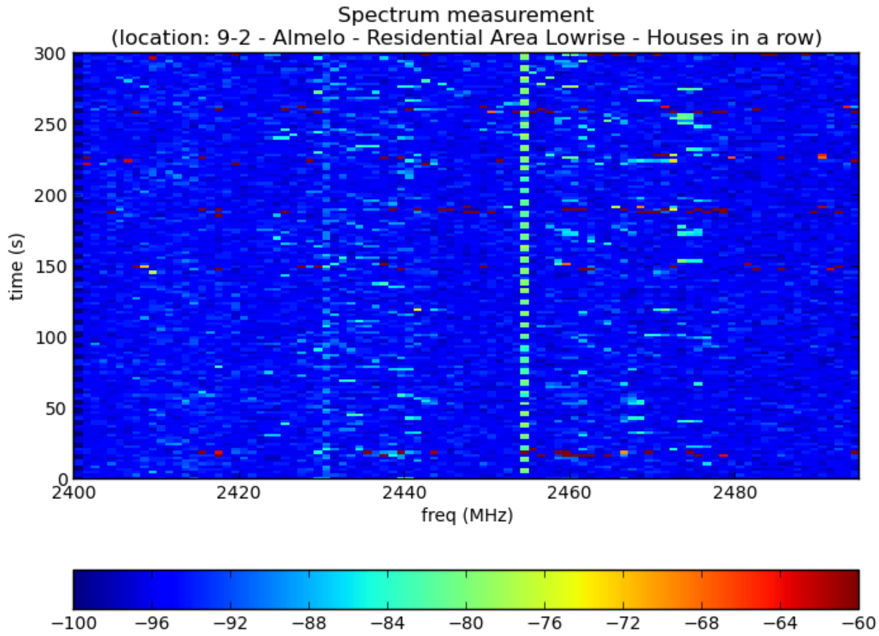

Figure 3.29: WiSpy measurement 2.4 GHz Residential low rise, location 9-2 (dBm)

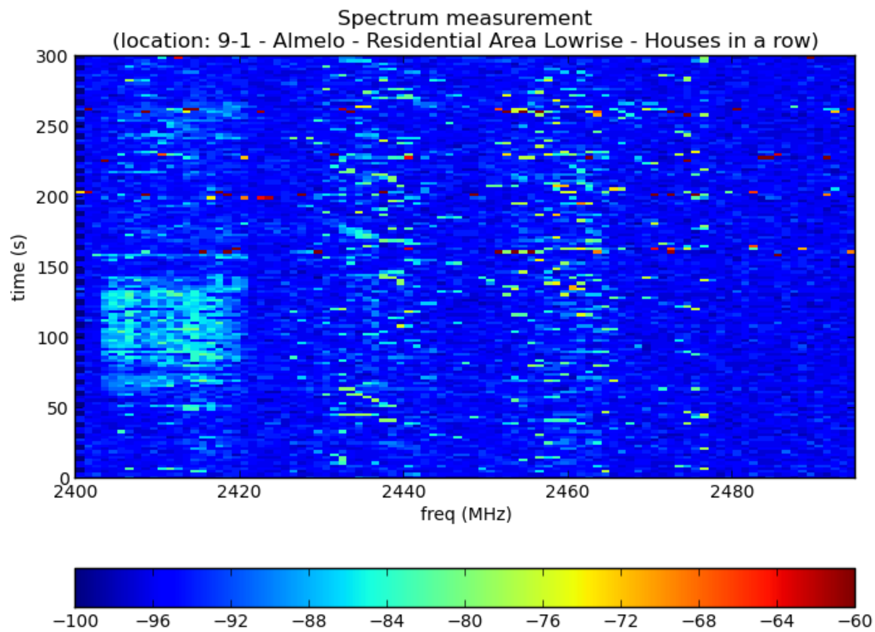

Figure 3.30: WiSpy measurement 2.4 GHz Residential low rise, location 9-1 (dBm)

3.8 AP Channel Distribution

The Access Point scans can also be used to evaluate if the limited available bandwidth on the 2.4 GHz band is effectively used. To determine this, the distribution of used channels can be reviewed.
Figure 3.31 shows the distribution of all Access Points seen in all measurements. Access Points are uniquely identified by their SSID, which is also used to filter out Access Points of the WiFi hotspot network of Ziggo, UPC and KPN (FON). Looking at these distributions, considering that only three channels in the 2.4 GHz band are non-overlapping (see Figure 2.1), the three peaks on channels 1, 6, and 11 actually show a well distributed use of the 2.4 GHz band. Roughly 2/3 of all APs are on one of these three channels and 1/3 is on any other channel.

The results show that the alternative pattern of channel 1, 5, 9 and 13 is hardly used. Only the use of channel 13 is seen specifically. This pattern may cause a slight risk of interference between channels, but is suggested for Europe as the gain of the fourth channel is expected to be larger than this risk of interference. An important reason this is not used as much is due to the US spectral limitation that only allows up to channel 11.

Figure 3.32 shows the same information for the 5 GHz band. Here it can be seen that Access Points are distributed along the available channels, although not as evenly. This may be due to the fact that there are few problems experienced by users of the 5 GHz band currently, since it not used as intensively as the 2.4 GHz band. So there is less incentive for users to choose the optimal channel.

Figure 3.33, Figure 3.34, and Figure 3.35 give three typical examples of the distribution of Access Points in individual measurements. Again the figures show that the channels used for Access Points are distributed along the 2.4 GHz band. The distribution is more evenly in busier environments. It can be concluded that apparently WiFi users already choose channels to optimize their performance. This can be explained by the fact that changing channels is common knowledge and due to the fact that provider helpdesks advise their customers to take these measures in case of WiFi problems (for example explained by Prof. D Raedloosch, WiFicisus of Ziggo, http://verbeterwifi.ziggo.nl/).

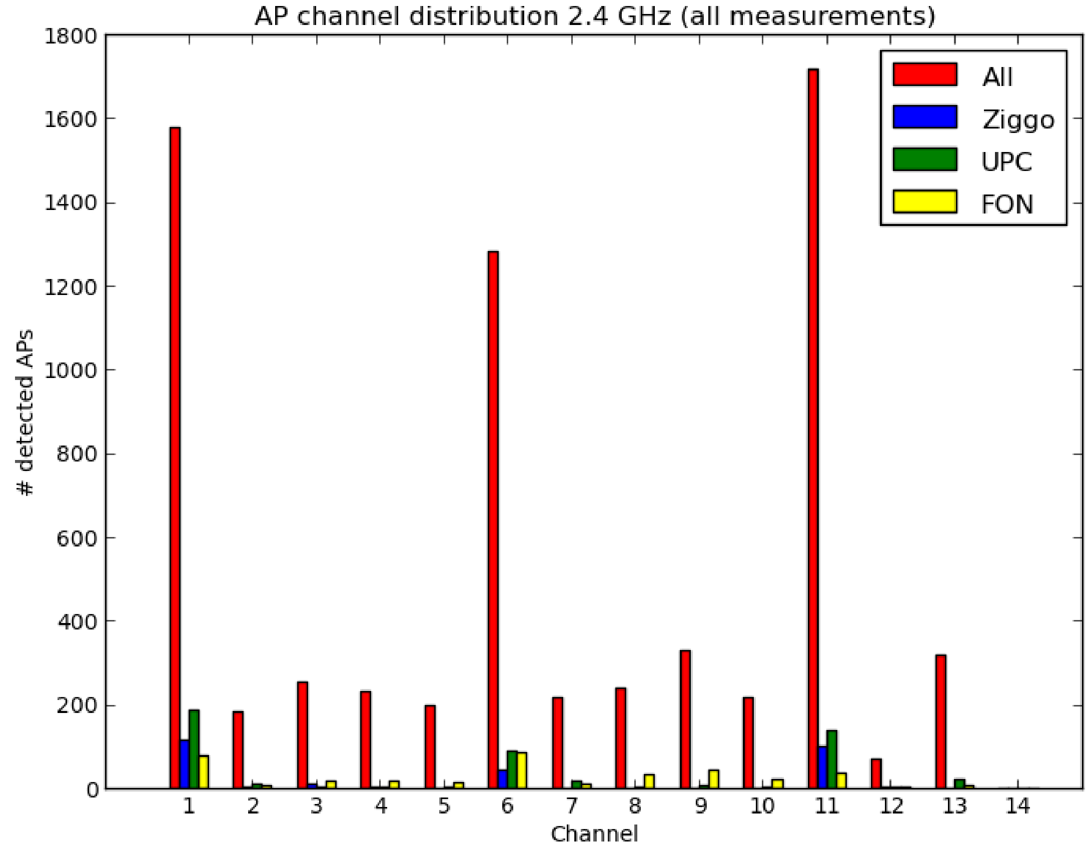

Figure 3.31: Distribution of Access Points across channels (cumulating all 2.4 GHz measurements)

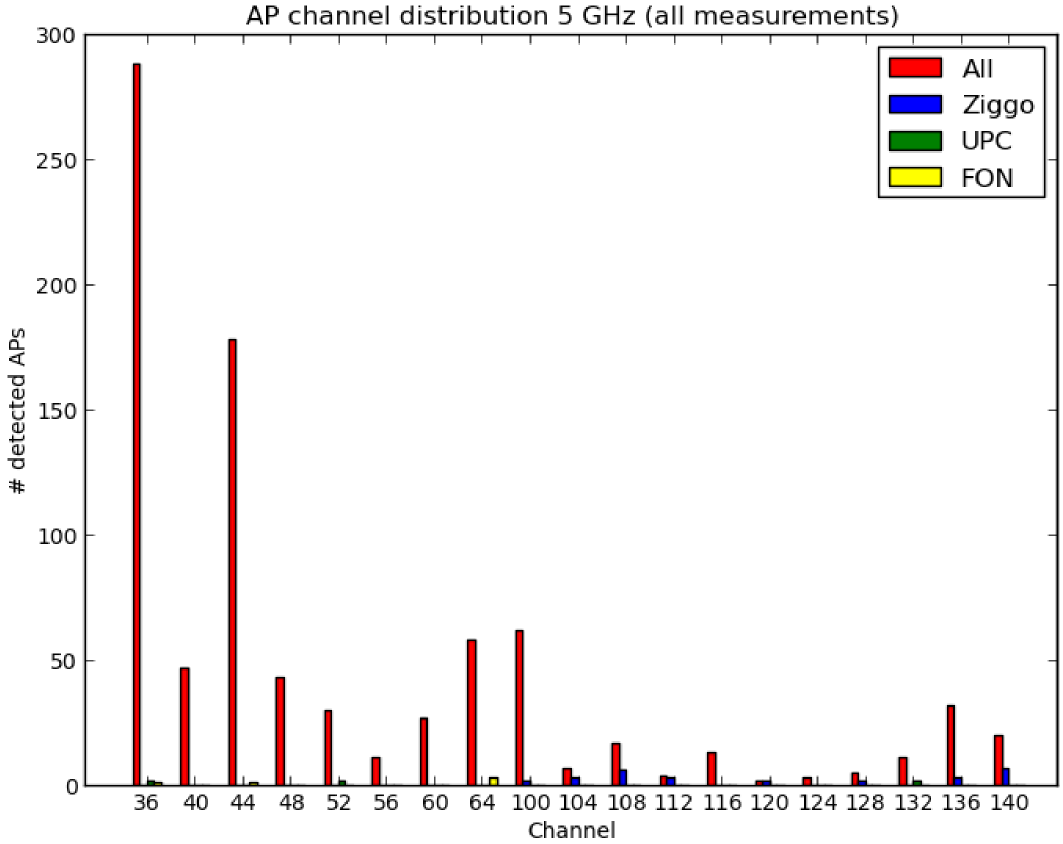

Figure 3.32: Distribution of Access Points across channels (cumulating all 5 GHz measurements)

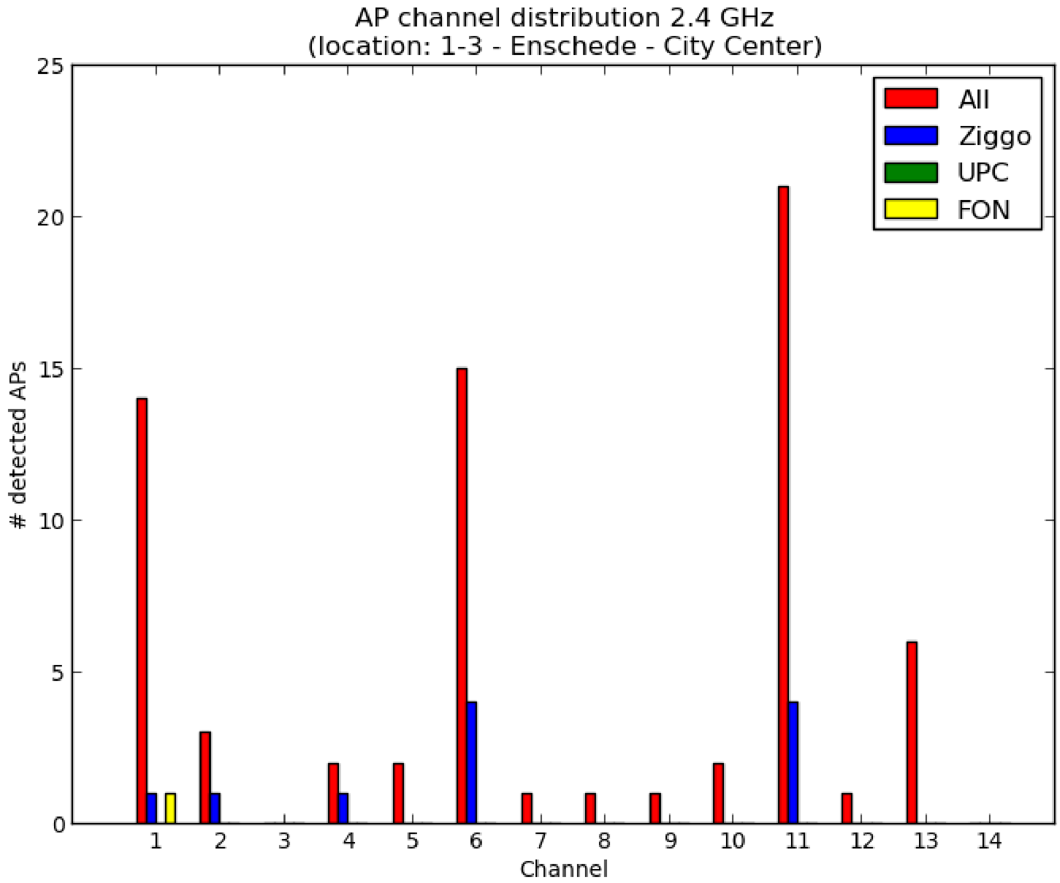

Figure 3.33: Distribution of Access Points across channels in measurement 1-3

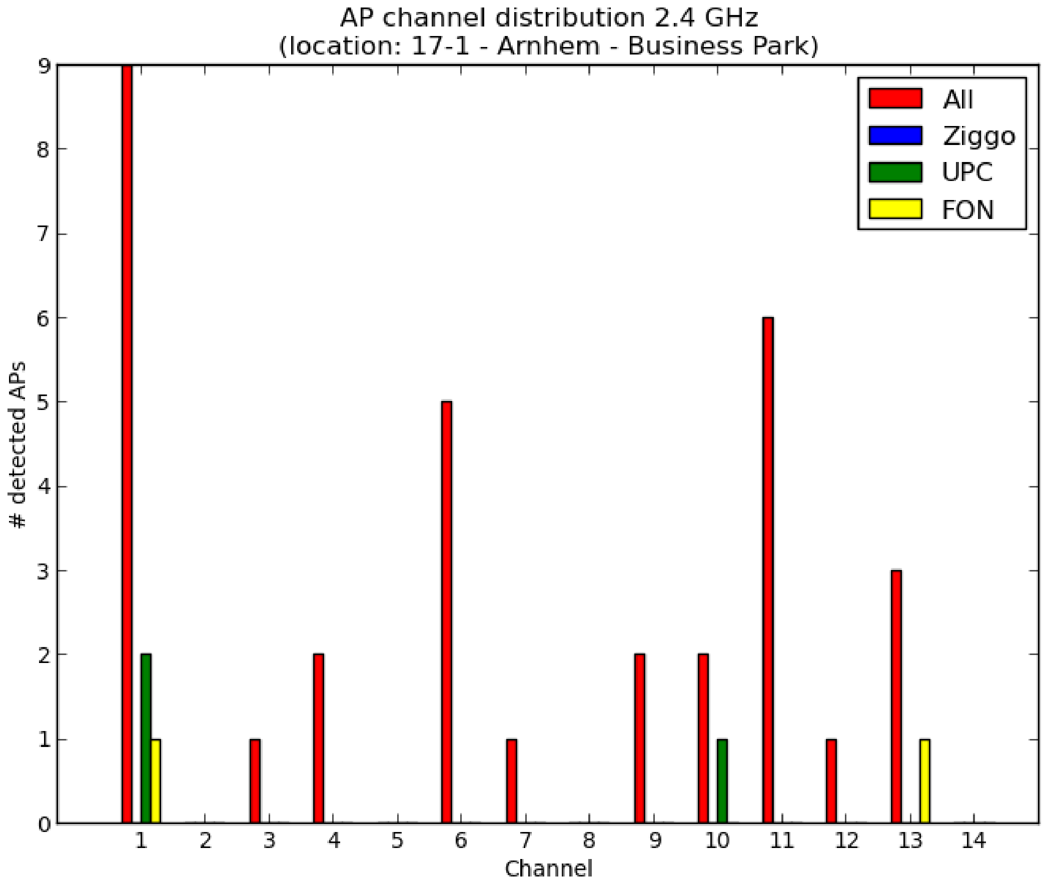

Figure 3.34: Distribution of Access Points across channels in measurement 17-1

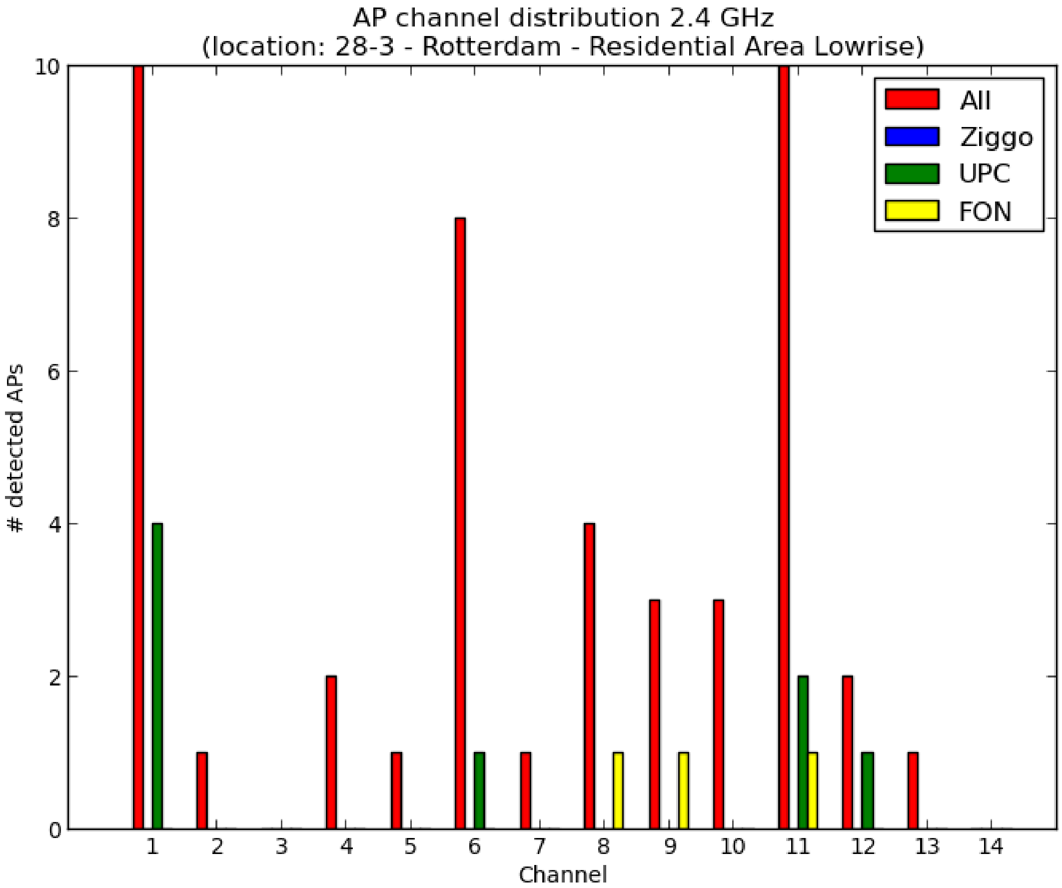

Figure 3.35: Distribution of Access Points across channels in measurement 28-3

3.9 Effect of WiFi-operators

In the previous section, the number of Access Points of the three major public WiFi operators were shown. One of the research questions was if the presence of these networks influence the use of the 2.4 GHz band. Because the cable operators Ziggo and UPC operate in different geographical areas, measurement locations were chosen in both areas. Locations were also chosen in cities where neither UPC nor Ziggo are present (e.g. Gouda and Borculo).

In Table 3.1 (paragraph 3.1), the measurement locations are related to the cable company. For example Enschede is Ziggo area, Rotterdam is UPC. A comparison between these areas can then be made. KPN has countrywide geographical coverage with FON public WiFi network, and this is also measured.

In Table 3.2 an overview is given per cable company area the total number of Access Points and the average number of Access Points per measurement. The number of APs is then calculated to the fraction of the total APs that were seen during scanning.

Provider	Total # APs				Average # APs / measurement				Fraction APs of total (%)		
	All	Ziggo	UPC	FON	All	Ziggo	UPC	FON	Ziggo	UPC	FON
Ziggo Area	1616	237	0	139	29.4	4.3	0	2.5	14.7	0	8.6
UPC Area	2438	0	428	142	39.3	0	6.9	2.3	0	17.6	5.8
Caiway Area	408	0	0	44	24.0	0	0	2.6	0	0	10.8

Table 3.2 Overview of public WiFi Access Points

Although a significant number of Access Points has been encountered, it was not possible to determine that there is significant performance difference between the geographical areas. There are too many other factors influencing the measurements to draw good conclusions from this data.
Another measurement which could theoretically be used to analyze the use of these networks is the frame sniffing. In sniffed data, the SSID of data frames could be used to identify individual frames. However, in this project, the measurements were short per location to allow for measurements on many location. Longer measurements would be required to analyze the actual use of these hotspots.

What is clear, is that the number of additional Access Points is significant. The public WiFi service of Ziggo consisted of 14.7% of the APs found in the measurement, for UPC 17.6% and for KPN FON around 7.2% of all measurements. In total 4462 APs were found, of which 990 APs belonged to public WiFi networks. All APs transmit beacon frames, so 22% of the beacon frames in the measurements are related to public WiFi networks.

3.10 Frame Types

The frame sniffing measurements were used to analyze the actual use of a WiFi channel. Note that these measurements were only performed with car measurements due to the size of the logger (see Figure 2.4).

Figures 3.36 and 3.37 show the average number of different frame types seen in the measurements. In these results it can be seen that the amount of data frames captured is low. Figure 3.38 and 3.39 show the same information, but then related to the amount of bytes (MB) that were captured.

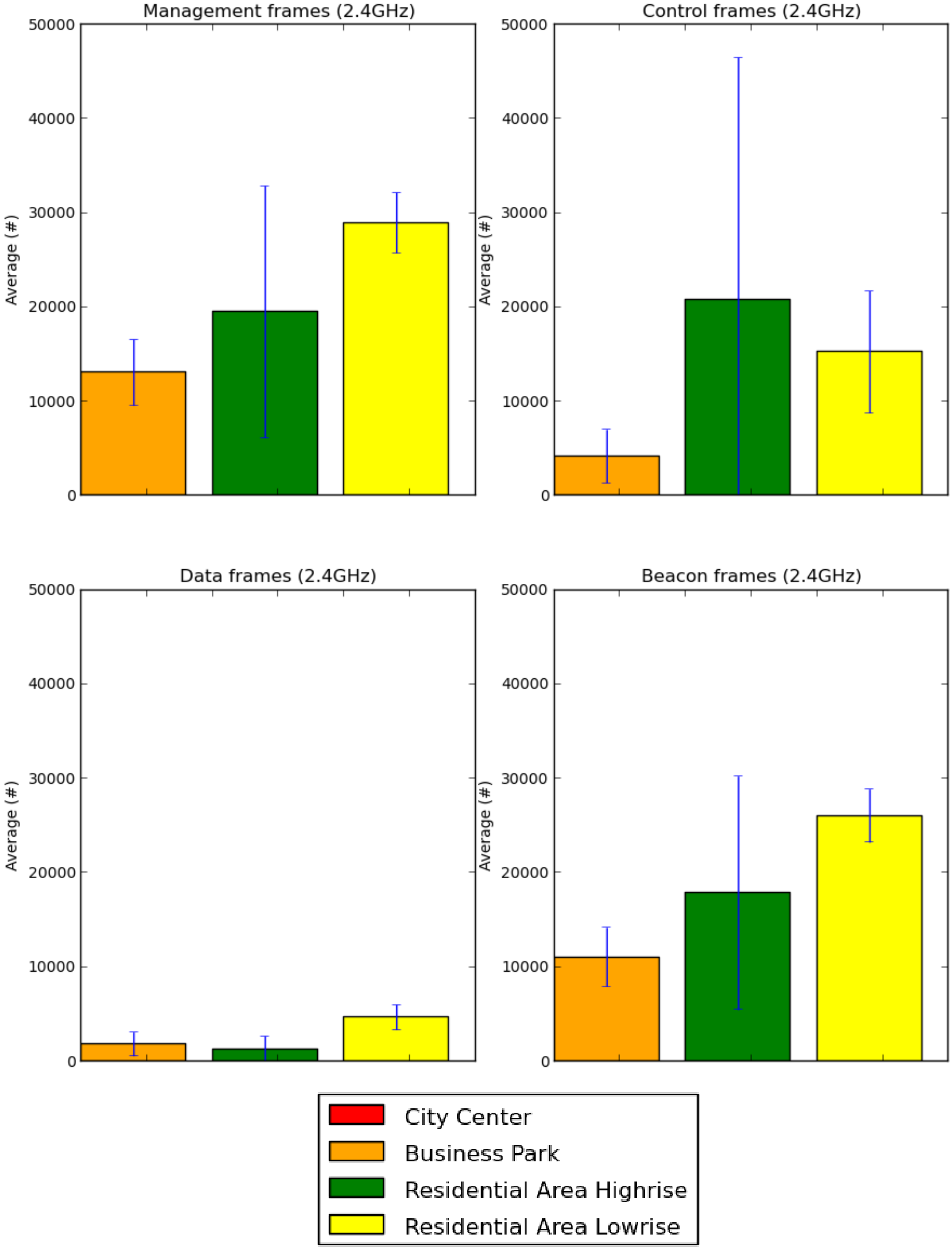

Figure 3.36: Average number of frame types 2.4 GHz per scenario

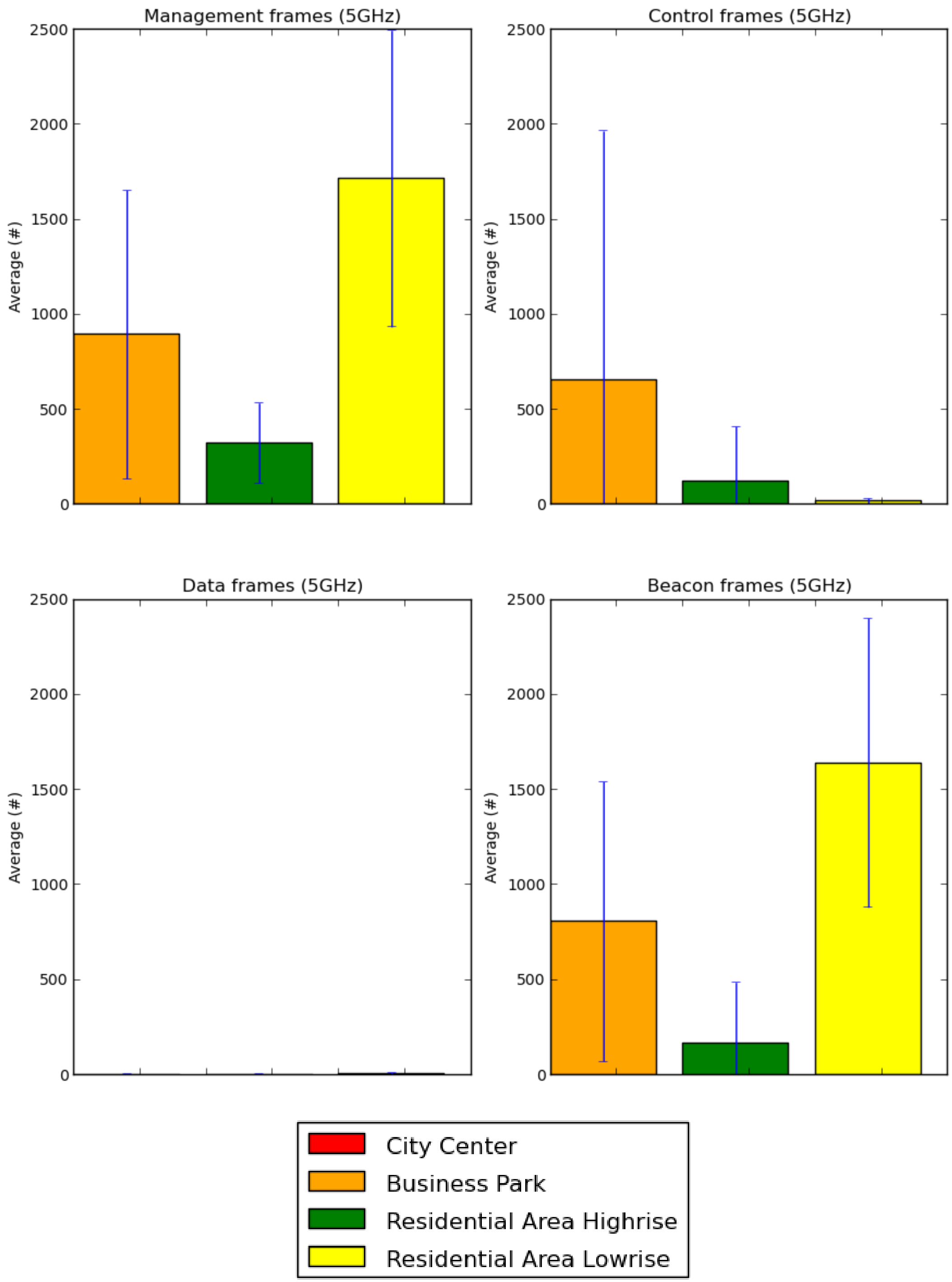

Figure 3.37: Average number of frame types 5 GHz per scenario

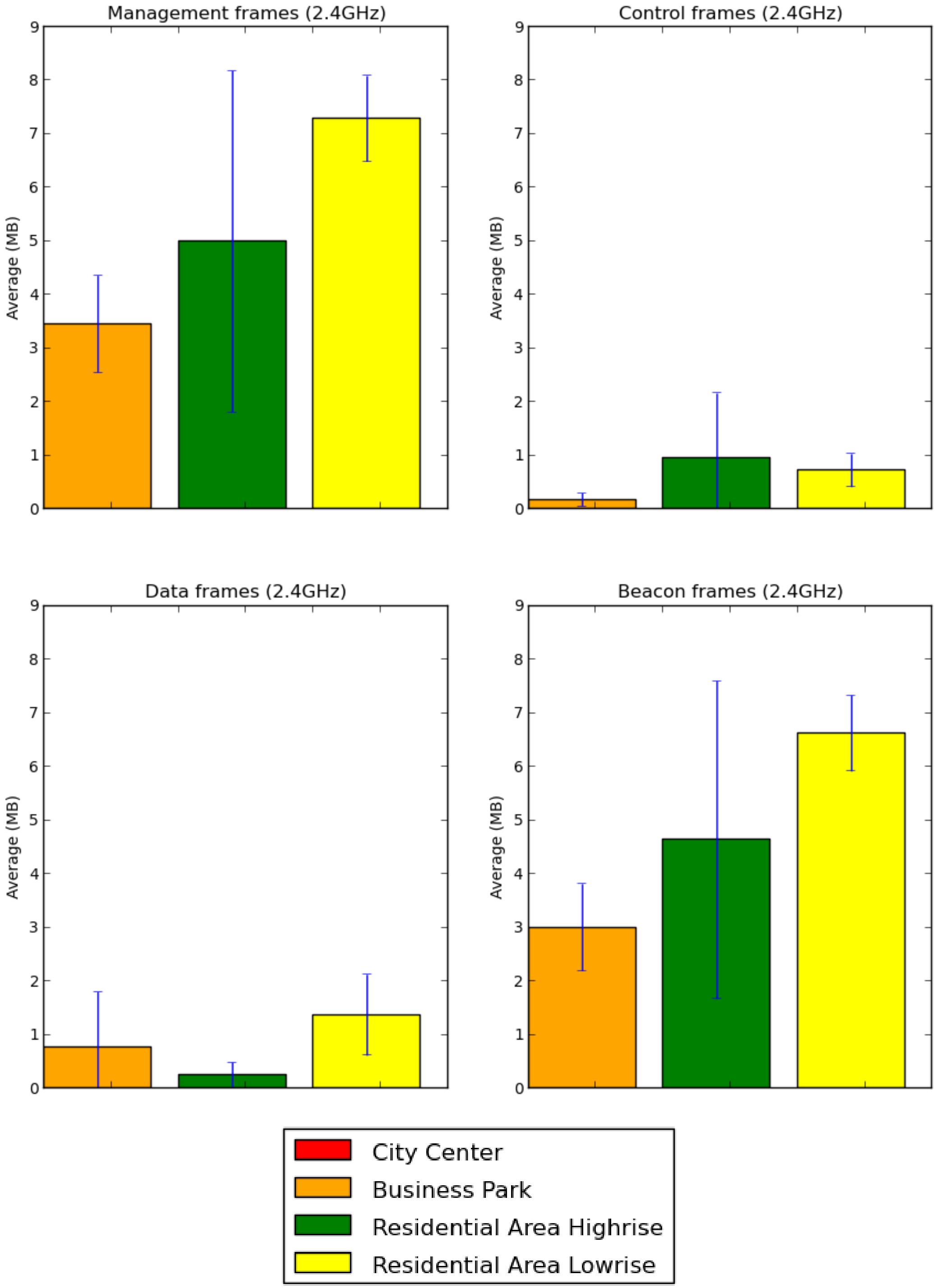

Figure 3.38: Average amount of data (MB) per frame type 2.4 GHz per scenario

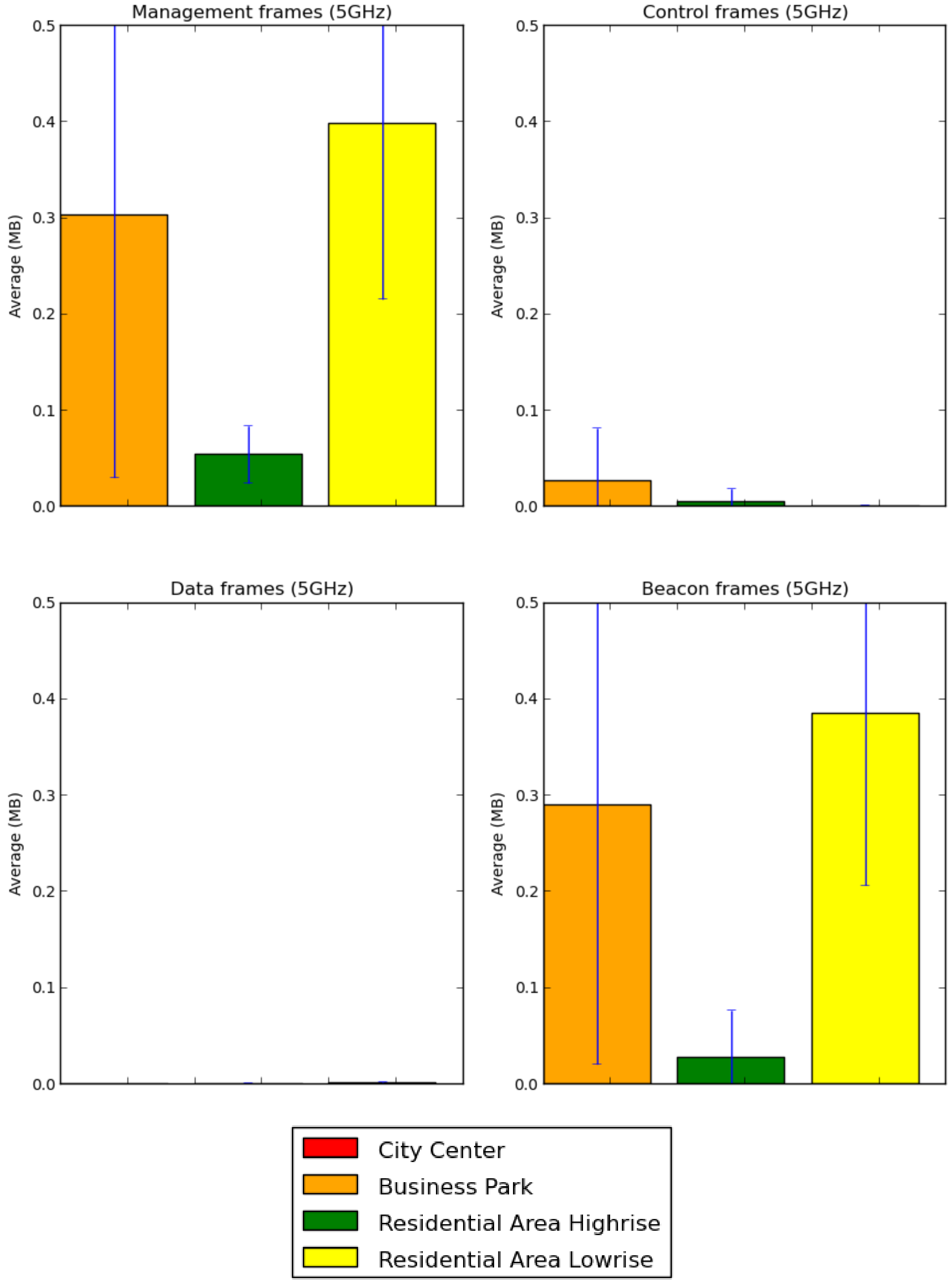

Figure 3.39: Average amount of data (MB) per frame type 5 GHz per scenario

By looking at individual measurements, it is concluded that the measurements were too short to gather enough data frames to perform extensive analysis. However, the results are very interesting by looking at the continuous amount of management overhead transmitted in WiFi networks. To analyze this, location 9-8 (Almelo) is taken as an example. This is also one of the few measurements where a significant amount of data frames were captured.

Figure 3.40 shows the number of frames per type or subtype that was captured. The three frame types shown in red combined are all captured frames. Of the subtypes only a subset is shown. It is shown in the graph that most of the frames are for management or control data, and only a small number of the frames is actual data. However, these overhead frames are typically smaller than data frames. The amount of bytes transmitted should also be taken into account, which is shown in figure 3.41. Now it can be seen that in bytes, the control data is much less, but the number of bytes used for management frames is still relative high.

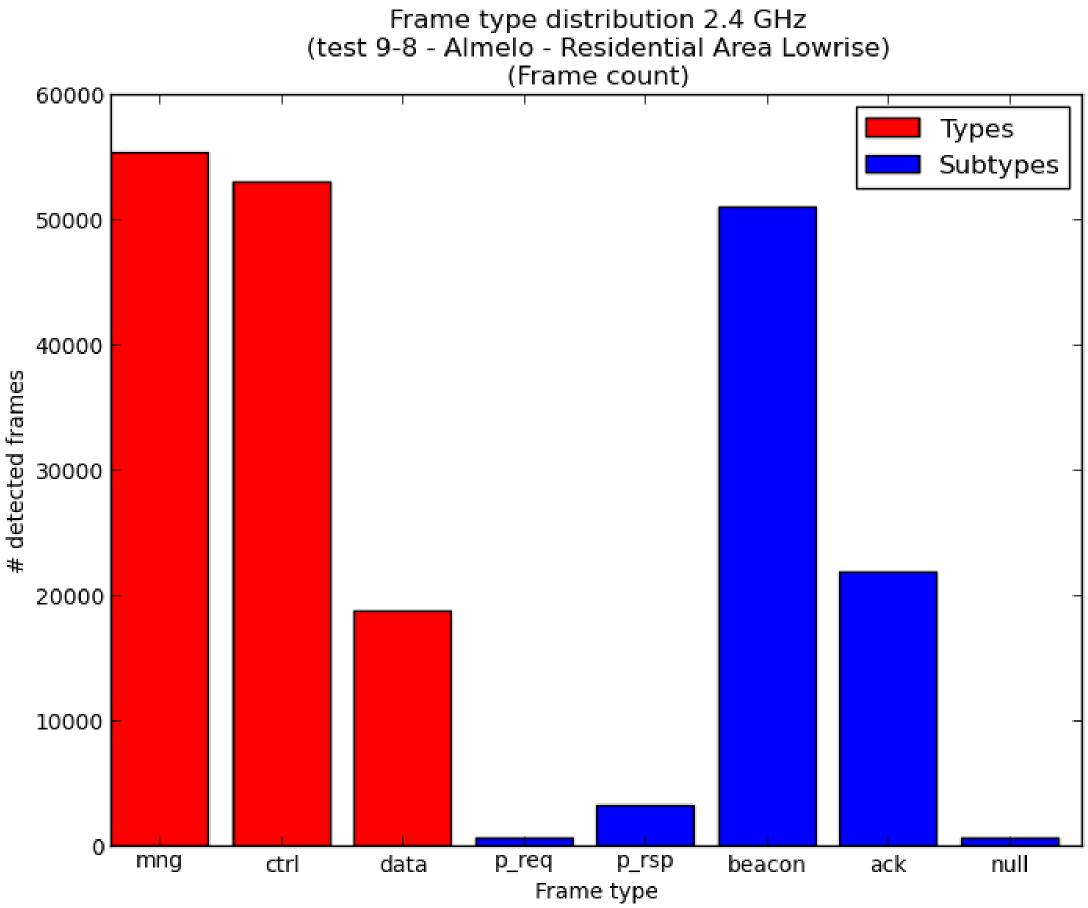

Figure 3.40: Number of frames captured in test 9-8, per frame type / subtype

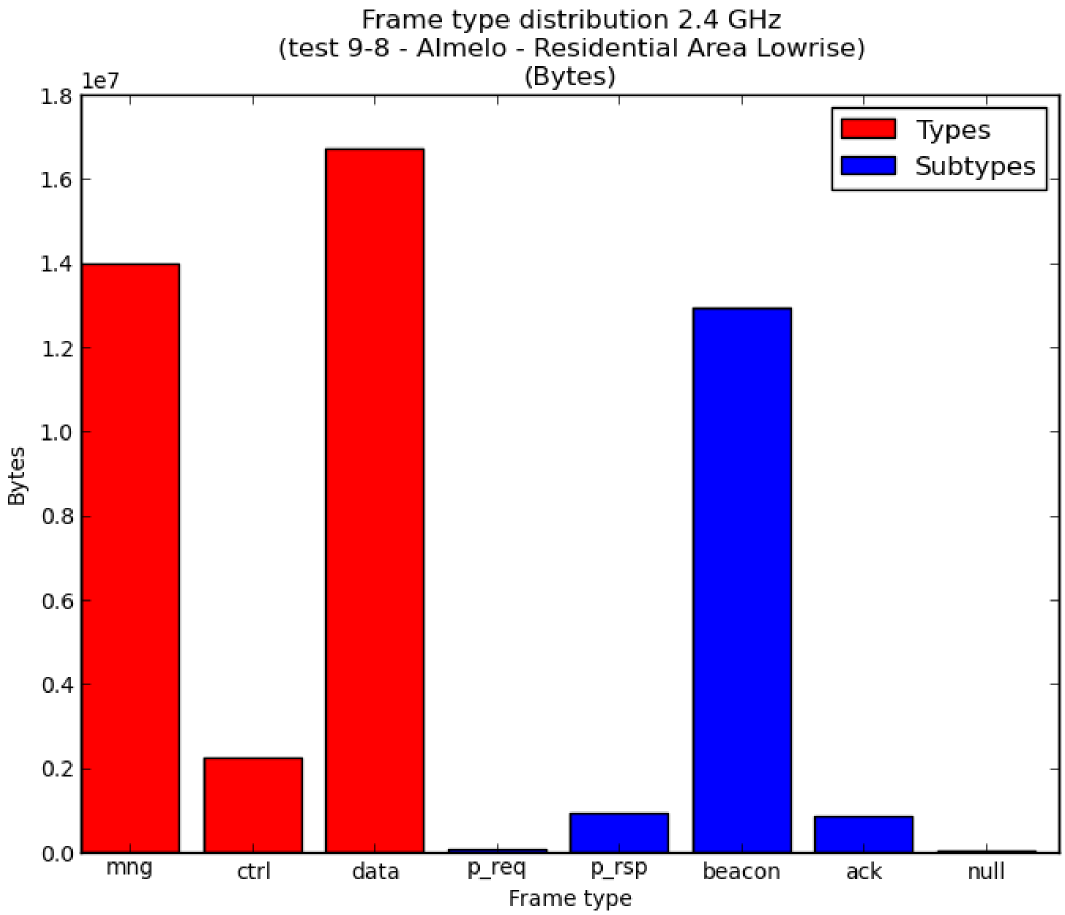

Figure 3.41: Bytes captured in test 9-8, per frame type / subtype

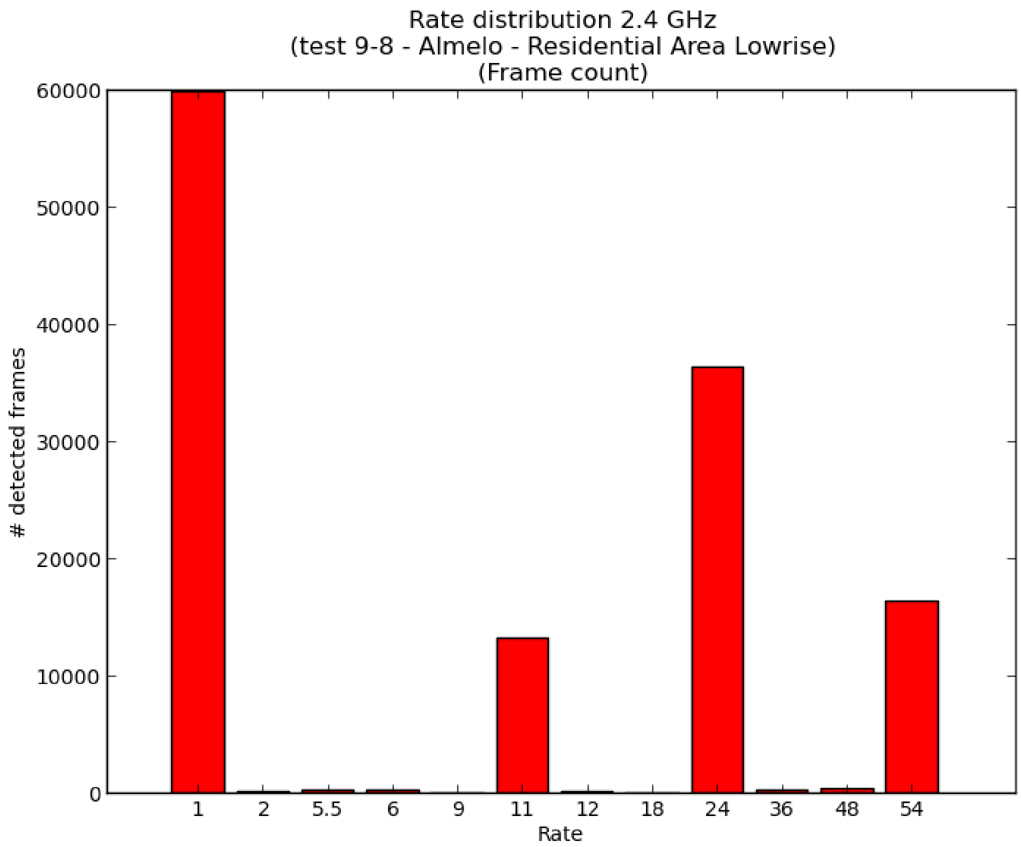

Figure 3.42: Number of frames captured in test 9-8, per data rate

Besides looking at frame types, it is also good to look at data rates (modulation scheme, see Table 2.2) at which the frames are sent. Figure 3.42 shows the amount of frames received per data rate. Again, it is not the absolute number of frames which is of interest, but much more when converted to “airtime” (i.e. how long is the spectrum occupied by a frame) used per data rate. This is shown in Figure 3.43, where it can be seen that over 40% of the time, frames at the lowest data rate are being send. Because of the information seen in Figure 3.40, that a significant part of the frames are beacons, the time needed for the beacon frames were calculated. This is shown in Figure 3.44, where it is seen that just the beacon frames use over 37% of the available airtime.

Multiple causes can be identified for this high number:

- The use of the lowest data rate of 1Mbps causes a long airtime being required to transmit one beacon. Sending beacons on this data rate is required because by default 802.11b support is still enabled on all Access Points (backwards compatibility).
- The high number of Access Points
- The beacon recurrence rate (typically each Access Point sends 10 beacons per second)

The distribution over the rates should be used with care. At lower rate packets travel further than packets at a higher data rate due to the difference in required signal to noise ratio.
On the other hand collisions are more likely to occur for lower data rates (lower modulation scheme) due to the length of bursts. So the measured distribution differs from the distribution of transmitted packets.

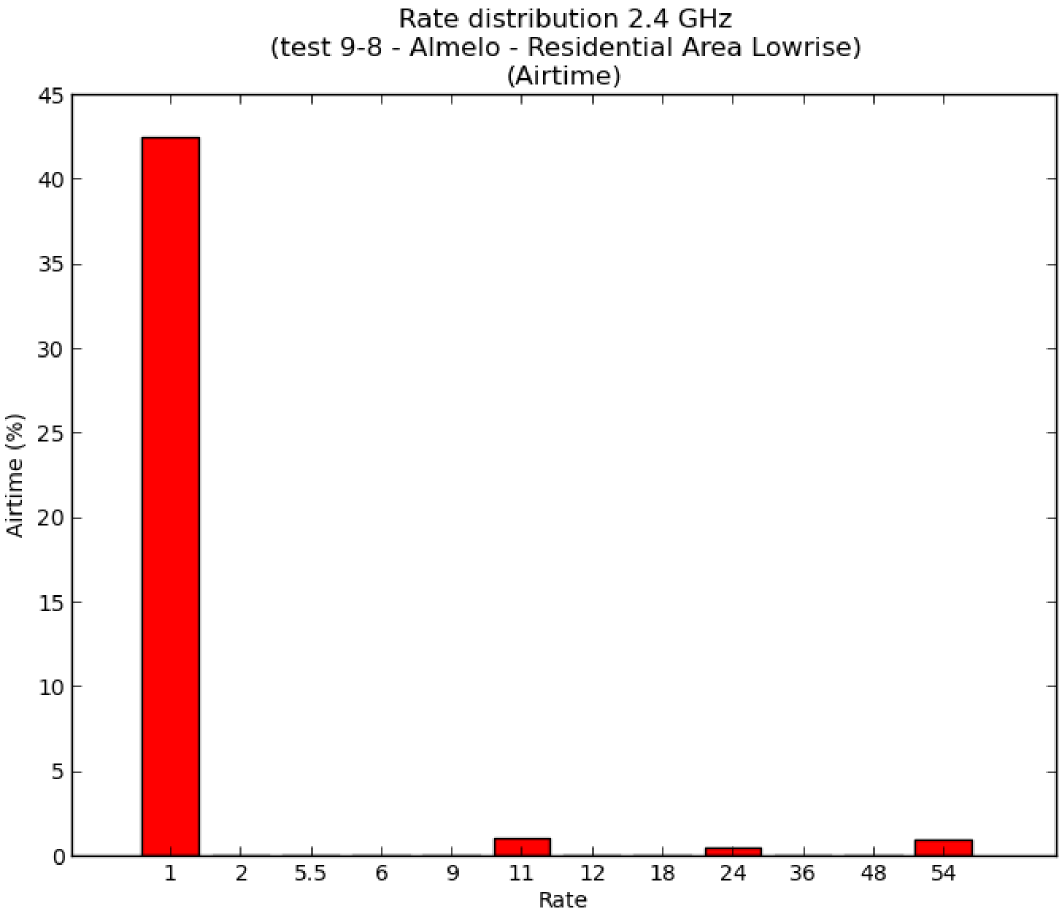

Figure 3.43: Fraction of total available airtime used per data rate in test 9-8

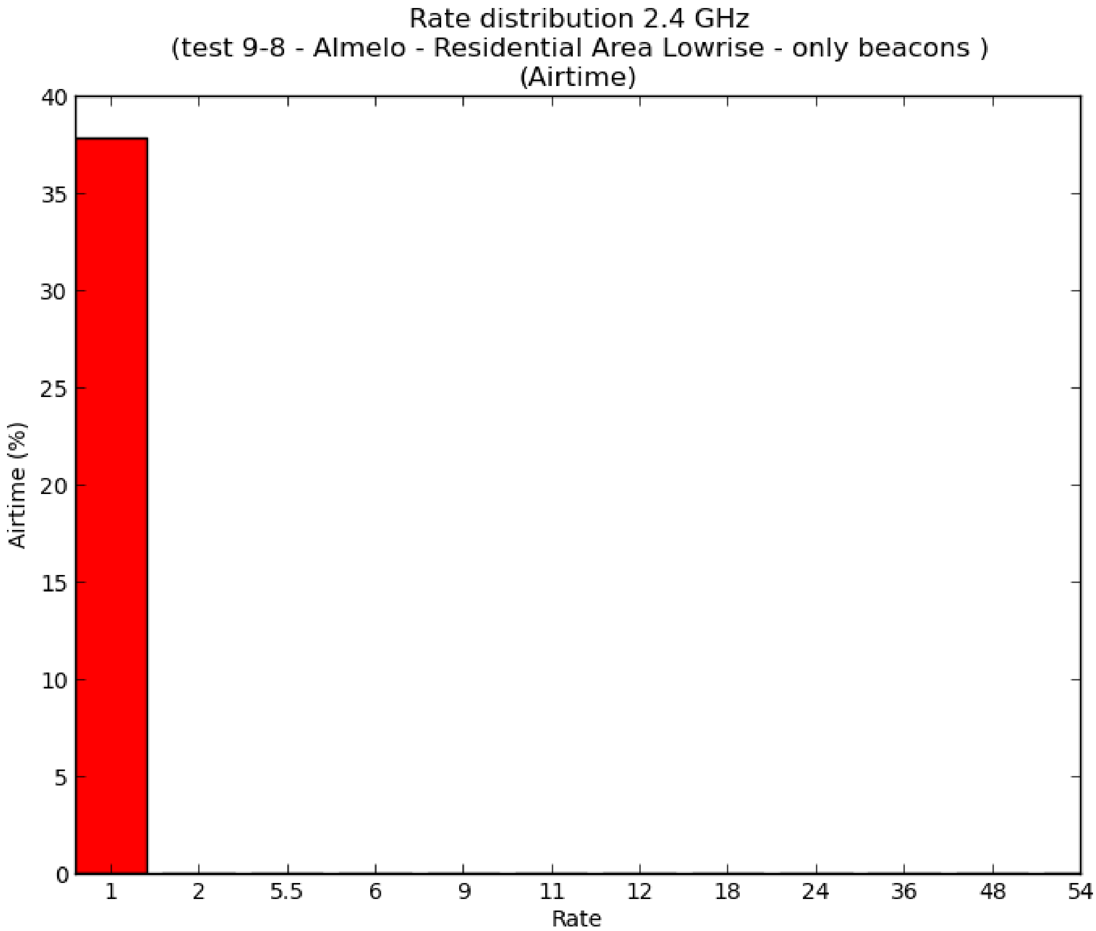

Figure 3.44: Fraction of total available airtime used per data rate for beacons in test 9-8

The high airtime used for beacons in this example can be seen in all measurements. As expected, the total airtime used by beacons correlates to the number of Access Points that are present, which is shown in Figure 3.45. Note that there are some effects that cause outliers and non-linearity in this plot. Not all beacons are correctly received by the sniffer, even if they do cause interference at the measurement point, due to hidden node problems. Also, the probability of collisions is higher when the number of Access Points increase.

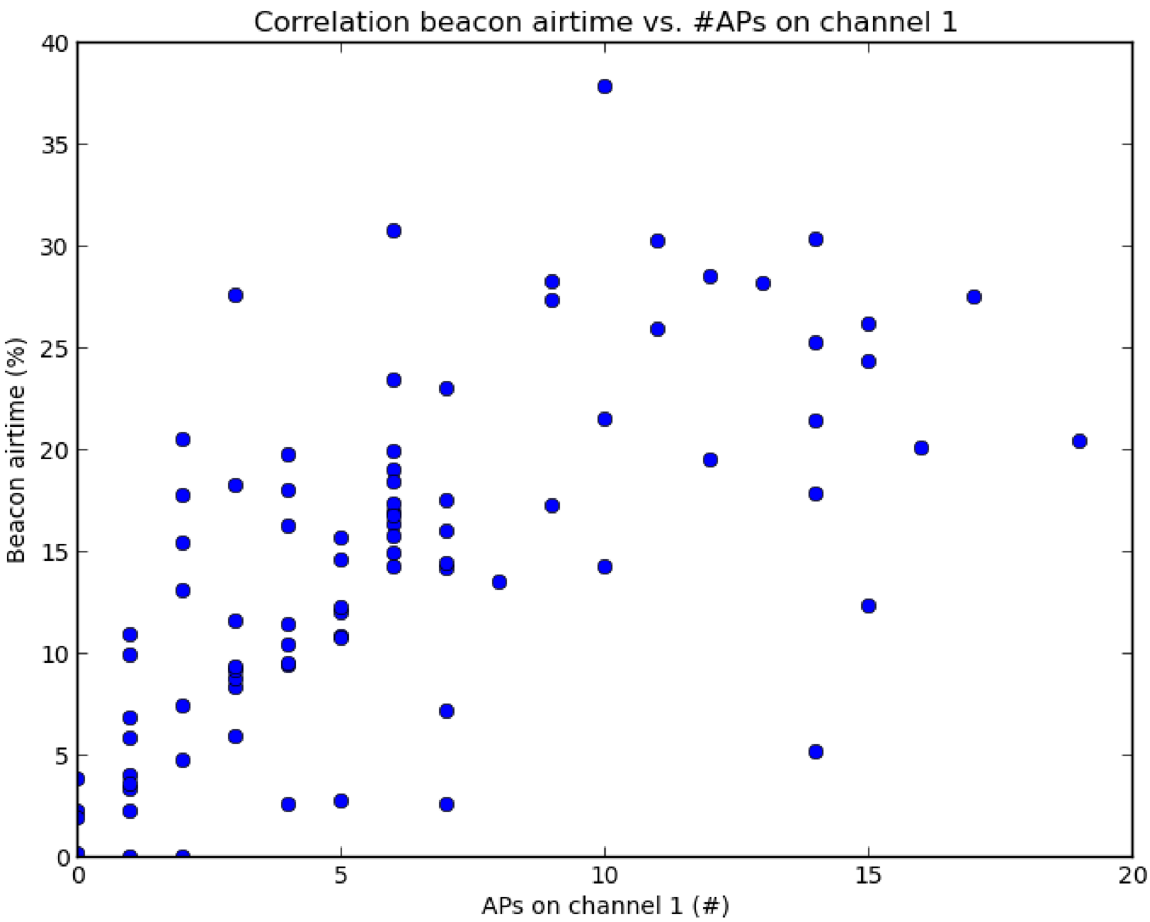

Figure 3.45: Correlation between number of detected Access Points and the airtime used by beacon frames

4 CONCLUSIONS

This chapter provides an overview of the most important conclusions based on the research that was performed. The conclusions are divided in overall conclusions (paragraph 4.1) and conclusions related to research assignment (paragraph 4.2).

4.1 Overall Conclusions:

1. There are locations where available capacity is severely limited and there is serious congestion. This is most often the case in City Centers, Shopping Malls and in dense Residential Areas (houses in rows, high rises).

2. Building a WiFi network is very simple and is becoming more and more common in every household. Many internet providers provide a wireless modem as part of the internet access service. There is no to need to apply for a license or authorization to install a WiFi Access Point (hence license exempt), helping in the rapid growth of wireless networks.

3. The range of the WiFi Access Points on 2.4 GHz is often greater than the household or business where it is installed, automatically creating interference for the other households or business. This was especially seen in dense Residential Areas and Shopping Areas. In the past couple of years, WiFi Range extenders have offered to users, adding to the number of wireless network devices. Because the number of user devices is continuing to grow (for example smartphones, tablets, streaming audio devices, smart TVs) and the amount of wireless data is growing each year by up to 50%, the WiFi congestion problems found on the 2.4 GHz band are expected to become worse.

4. Actual throughput of WiFi standards is much less than the maximum physical data rate that can be achieved in ideal situations. For 802.11g, the 54 Mbit/s translates to 21 Mbit/s in situations with little interference. This calculates to 39% percent net throughput. The lower throughput also applies to 802.11n. This is partly caused by the overhead needed to control transmissions and partly because even in situations with little interference, radio circumstances are hardly ever ideal. Transmission time needs to be shared with all other users in the surrounding area that are on the same channel. The resulting data speed is perhaps only 10 – 20% of the advertised bandwidth even when there is little congestion.

5. Based on experience, modern households consisting of 2 or more persons can easily contain 10 or more WiFi enabled devices. This shows the success of this technology. In principle, an Access Point can handle traffic for all these devices at the same time. However when neighboring networks and traffic also have impact on available transmission time (and this was measured in this research), congestion can easily happen.

6. WiFi uses CSMA/CA as scheduling mechanism. Because of this, relative high transmission time needs to be reserved to provide access to users that arrive at random times. This is also part of the reason that the OFCOM report [ref 6] calculates high usage of WiFi when the spectrum is used for more than 20%.

7. A lot of airtime is taken up by the large number of beacons transmitted by the Access Points. In some measurements, more than 37% of the time beacons are being transmitted. These beacons are always transmitted on the lowest data speed (1 Mbit/s) and have the longest reach, causing more interference than needed.

8. Access points are by default backwards compatible. In some APs, backwards compatibility with 802.11b and 802.11g (legacy standards) cannot even be switched off. The backwards compatibility reduces the amount of airtime available for data transmission as management frames are all transmitted at the lowest rate the AP supports.

4.2 Conclusions related to Research Assignment

In paragraph 1.2 the questions related to the research assignment can be found, these were the original starting for the investigation. In paragraph 2.2 the research methodology is described, resulting a measurement setup related to the assignment questions.
The **first two research questions** are: (1) which measurement setup is able to determine congestion and interference, taking into account current scientific knowledge and best practices; (2) which metrics are the most relevant to assess the status of an area type?

9. One good way of measuring occupancy and congestion on the license exempt 2.4 GHz and 5 GHz band, is by performing a data throughput test. This relates to the effective achievable throughput in the typical environment to the net throughput for an interference free environment. It reflects best how a typical WiFi user would experience the radio environment.

10. The number of Access Points correlate to the throughput measurements, but a high number of Access Points does not automatically mean that the WiFi band is congested.

11. When looking at the number of Access Points found and available airtime, there is significant correlation. When there are more than 5 APs detected, the Beacon airtime increases to more than 15%. If there are more than 10 APs detected, the Beacon airtime is on average around 25%. This has impact on maximum throughput, due to lack of available airtime.

The **third question** is: (3) based on the measurements, what are the results per area type of the 2.4 GHz and 5 GHz bands? The results are given in in detail in paragraphs 3.3 till 3.6. Overall the results per area type are shown in Figure 3.4 for 2.4 GHz and in Figure 3.5 for the 5 GHz band. The

City Centers and Residential low rise show the lowest data throughput. A conclusion related to this:

12. Congestion correlates to the type of environment, but with significant variation. The performance at very similar locations can differ significantly. This variation correlates to the behavior of (a group of) individual users.

The **fourth question** is: (4) what is the measured impact on the area types and 2.4 GHz / 5 GHz frequency bands of public WiFi-operators like Ziggo, UPC and KPN?

13. The public WiFi operators (KPN, Ziggo, and UPC) can be clearly measured, but there is no direct relation between their presence and higher or lower interference. Only the number of networks (SSIDs) is higher because of by these operators, creating significant more overhead for beacon transmissions. In total 22% of the beacon transmissions are related to public WiFi operators.

The **fifth assignment question** is: (5) which important interference types of WiFi can be derived from the measurements (MAC and PHY layers)? This is also discussed in paragraph 2.2.5. Related to non-WiFi sources:

14. Spectrum measurements clearly show non-WiFi activity. This creates interruptions for WiFi traffic, but in the measurements it is not seen as problematic.

The **sixth question** is: (6) how is the 5 GHz band developing compared to the 2.4 GHz band? How many nodes can be found in the 5 GHz band compared to the 2.4 GHz-band? What is the actual use of the 5 GHz band in comparison with the 2.4 GHz band?

15. Considering measuring in typical urban or suburban environments, on the 2.4 GHz band, in nearly 20% of all the measurements the available data speed was considered bad or very bad. All other measurements (for example the number of Access Points found) align to the outcome of the throughput tests.

16. The 5 GHz band shows much fewer Access Points or RF signals compared to the 2.4 GHz band. These results seem realistic, but are probably also caused by the public locations used for the measurements and the shorter range of 5 GHz (roughly half compared to that of 2.4 GHz). No congestion was seen on the 5 GHz band, 91% of the throughput tests resulted in 'very good' and 9% resulted in 'good' results.

17. A location with severe congestion of 2.4 GHz was one of the few locations with significant 5 GHz traffic.

18. All measurements were performed in public areas and mostly on the street. The mobile measurements (using a laptop and backpack) were made closer to the Access Points and

show more interference.

19. The distribution of channels used for APs show that the entire 2.4 GHz band is used. Channels 1, 6, and 11 are preferred. There is significant use of channels in between. Channel 13 is seldom used.

5 RECOMMENDATIONS

Looking back at the measurements performed and the analysis and conclusions based on the results of the tests, some recommendations can be made.

1. Overall, there is significant interference at many locations. Based on this conclusion, it is recommended to use important services only on the 5 GHz band. Users that experience congestion are also advised to move to the 5 GHz band if possible.

2. Further investigation should be performed in how to limit the amount of interference created by other WiFi networks within Businesses and households. Perhaps this can be done by lowering output power.

3. The 2.4 GHz channel pattern 1-6-11 is mostly used. The European spectrum allocation also allows for the 1-5-9-13 pattern. It should be investigated whether the latter pattern would increase the actual throughput, and if so, how this pattern could be programmed onto the equipment.

4. Backwards compatibility should be restrained to situations that really require this. So default setting should be 802.11n only as much as possible. If possible, backward compatibility to 802.11g, without backward compatibility to 802.11b would be an alternative. Backward compatibility to 802.11b should be avoided as much as possible.

5. Typically each Access Point sends 10 beacons per second (at the lowest data rate, for backwards compatibility). It is recommended to investigate how this recurrence rate can be lowered, because it seems unnecessarily high. This could release more airtime for data transport.

6. It is recommended to regularly investigate the state of the license exempt spectrum to monitor traffic growth and number of networks. The traffic will continue to grow and this will impact available capacity.

7. This research project was focused on providing measurements over many locations and provide answers to the most important research questions. However, the measurement data contains much more information that cannot be fully discussed here. It is recommended to spend more time on more detailed analysis, possibly aided by additional measurement to better understand results.

8. Round trip time for IP packets over the wireless connection is a very interesting metric. However, the current measurements were too short to gather good statistical data. Longer measurements in busy environments would provide a much more detailed view of the user experience in congested WiFi networks.

9. At some locations, more preparation time should be reserved to obtain permission to measure (e.g. in entertainment areas, indoor business buildings). On several planned locations it was not allowed to perform the measurements, because it is seen as impacting the connections or hacking the network.

10. It is recommended to further investigate the source of the repetitive vertical interference patterns in some WiSpy measurements. This happened on several locations.

11. It is recommended to perform measurements from inside residential high rise buildings and low rise buildings to better determine the occupancy of the 2.4 GHz and 5 GHz band.

12. In some locations, the average performance is lower than expected (e.g. significantly different from other locations of the same type). It is recommended to perform more investigation of the locations where this is found. This can perhaps help in creating better understanding of causes for congestion.

13. Mobile Network operators have been investigating the possibility of WiFi 'data-offload', to lessen the load on 3G and 4G networks. Based on the current usage of WiFi in City Centers and the congestion found in these areas, mobile data offloading is not thought to be a viable option in many cases.

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