Wi-5

**What to do With the Wi-Fi Wild West**

Horizon 2020
European Union Funding
for Research & Innovation

| | |
|---|---|
| Deliverable | D2.2 |
| Title | Wi-Fi Optimisation Solutions Roadmap |
| Date | December 2016 |
| Milestone | MS4 |
| Authors | Frank den Hartog (DoVes Research, Editor), Alex Popescu (TNO), Miodrag Djurica (TNO), Pia Kempker (TNO), Alessandro Raschella (LJMU), Mirghiasaldin Seyedebrahimi (LJMU), Ali Arsal (Airties) |
| Reviewers | Michael Mackay (LJMU), Qi Shi (LJMU), Faycal Bouhafs (LJMU), Jan de Nijs (TNO) |
| Approved by | General Assembly |
| Dissemination | Public |

Abstract

The two main contributions of this deliverable are:

1) A roadmap showing the need for optimisation as experienced by the user over time versus the optimisation offered by the various proposed wireless technologies, including Wi-5. It is largely based on the evolution roadmap of IEEE802.11, as from a survey among six European operators we concluded that by and large they intend to keep following the Wi-Fi Alliance product roadmap with regard to their Wi-Fi deployment plans, given the needs of their customers.
2) The results of our quantitative modelling of the dense apartment use case regarding various spectral efficiency performance indicators, such as throughput per apartment, and average throughput for the complete apartment block. The results show that for this use case the Wi-5 solution provides a significant improvement in spectral efficiency compared to the current situation where everybody freely chooses a channel or there is limited automatic channel selection performed by the Access Point (AP).

## Wi-5 Consortium


| | | |
|---|---|---|
| LIVERPOOL JOHN MOORES UNIVERSITY | Liverpool John Moores University | 2 Rodney Street<br>Egerton Court<br>Liverpool, L3 5UK<br>United Kingdom |
| TNO | Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek | Anna van Buerenplein 1<br>2595 DA Den Haag<br>Netherlands |
| Universidad Zaragoza 1542 | Universidad de Zaragoza | Calle Pedro Cerbuna 12<br>Zaragoza<br>50009<br>Spain |
| AirTies | AirTies Kablosuz İletişim San. ve Dış Tic. A.Ş. | Mithat Uluünlü Sokak No:23<br>Esentepe, Şişli<br>P.K 34394<br>İstanbul<br>Turkey |

# Contents

## Executive Summary

Spectrum is a scarce public resource whose usage is often strategic for the economy and society, and which must be optimised in view of the expected exponential growth in traffic and usages. Wi-Fi forms a special case as it uses unlicensed unmanaged spectrum. In this context, the Horizon 2020 Wi-5 (What to do With the Wi-Fi Wild West) project proposes an architecture based on an integrated and coordinated set of smart solutions able to efficiently reduce interference between neighbouring Wi-Fi Access Points (APs) and provide optimised connectivity for new and emerging services.

This deliverable answers two research questions:

1) Would a solution such as Wi-5 fit into the roadmaps that operators and vendors are currently using for their Wi-Fi deployment?
2) Can we quantify the effect that the Wi-5 solutions have on the actual performance of Wi-Fi systems as used in the current use cases?

Regarding the first question, we conducted a survey among six European operators. From the survey, we can conclude that by and large the operators intend to keep following the Wi-Fi Alliance product roadmap with regard to their Wi-Fi deployment plans, given the needs of their customers. It can therefore be safely stated that the operators' Wi-Fi roadmap is just an extension of the IEEE 802.11 and Wi-Fi Alliance technology roadmaps.

Wi-5-like solutions can fit into the operators' Wi-Fi roadmaps, because:

- In earlier work we have already shown that viable business models exist for successful deployment of Wi-5,
- Even though most of the operators consider the 5 GHz band as a solution to the current congestion in the 2.4 GHz band, the outcome of the survey indicates that they also welcome the idea of managing the existing 2.4 GHz Wi-Fi environment better than what is done today. The latter is what Wi-5 is promising to deliver,
- It is not an unreasonable to assume that Wi-5-like solutions might become part of the future IEEE 802.11 and Wi-Fi Alliance roadmaps, as management solutions (e.g. 802.11k) are already part of their roadmap, and also Software Defined Networking (SDN), a basic building block of the Wi-5 architecture, is already well accepted by the industry.

Regarding the second research question, we performed a first quantitative modelling of the dense apartment deployment use case regarding various spectral efficiency performance indicators, such as throughput per apartment, and average throughput for the complete apartment block. This is the first time that such a Wi-Fi performance evaluation is done for a 3D environment.

The simulations clearly indicate that over-congestion is indeed a problem in current dense apartment block Wi-Fi deployments. Current non-collaborative channel selection procedures typically lead to very destructive adjacent channel interference. Although there is anecdotal evidence in the literature that Wi-Fi congestion and over-congestion is an issue in dense apartment blocks, this is the first time that the issue is scientifically demonstrated and quantified.

AP operators agreeing with each other on an intuitive channel distribution avoiding adjacent channel interference already provides significant performance improvement in most of the apartments. However, it may also lead to a grossly unfair distribution of resources over the individual apartments. This issue is then ultimately solved by applying the Wi-5 channel selection algorithm.

In theory, the algorithm can be applied “offline”, i.e. people manually configure their APs according to the obtained channel distribution. However:

- the optimal distribution will change over time, which would require repetitive manual configuration,
- many people do not know how to configure their APs,
- even better results can most likely be obtained by also taking transmit power, hand-over, and packet grouping functionalities into account, which are even harder to configure manually.

We therefore recommend that the optimisation algorithm is run in real-time on an intelligent central controller which automatically configures the APs, like the platform that is being developed in the Wi-5 project.

## Abbreviations

| | |
|---|---|
| **3D** | Three-Dimensional |
| **3G** | Third Generation mobile networking |
| **4G** | Fourth Generation mobile networking |
| **AP** | Access Point |
| **BT** | British Telecom |
| **CCK** | Complimentary Code Keying |
| **CSMA/CA** | Carrier Sense Multiple Access / Collision Avoidance |
| **CTO** | Chief Technology Officer |
| **CW** | Contention Window |
| **DCF** | Distributed Coordination Function |
| **DFS** | Dynamic Frequency Selection |
| **DT** | Deutsche Telekom |
| **EDCA** | Enhanced Distributed Chanel Access |
| **EN** | Exposed Node |
| **GMD** | Geometric Mean Decomposition |
| **HCF** | Hybrid Coordination Function |
| **HN** | Hidden Node |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **IT** | Information Technology |
| **LAN** | Local Area Network |
| **LOS** | Line-Of-Sight |
| **MAC** | Medium Access Control |
| **MIMO** | Multiple-Input Multiple-Output |
| **ML** | Maximum Likelihood |
| **MU-MIMO** | Multiple-User MIMO |
| **NLOS** | Non-LOS |
| **OFDM** | Orthogonal Frequency Division Multiplexing |
| **PHY** | PHYsical layer |
| **QoE** | Quality of Experience |
| **QoS** | Quality of Service |
| **RF** | Radio Frequency |
| **RRM** | Radio Resource Management |
| **SDN** | Software-Defined Networking |
| **SDM** | Spatial-Division multiplexing |
| **SIC** | Successive Interference Cancellation |
| **SISO** | Single-Input Single-Output |
| **SME** | Small and Medium Enterprise |
| **SOHO** | Small Office Home Office |
| **SSID** | Service Set IDentifier. |
| **STBC** | Space-Time Block Coding |
| **SU-MIMO** | Single-User MIMO |
| **TPC** | Transmit Power Control |
| **TV** | TeleVision |
| **TxBF** | Transmit BeamForming |
| **UNII** | Unlicensed National Information Infrastructure |

| | |
|---|---|
| **USA** | United States of America |
| **VHT** | Very High Throughput |
| **Wi-5** | What to do With the Wi-Fi Wild West |
| **Wi-Fi** | Wireless Fidelity |
| **WLAN** | Wireless Local Area Network |

# 1 Introduction

## 1.1 Wi-5 background

The last few years have witnessed a significant increase in the use of portable devices, especially smartphones and tablets thanks to their functionality, user-friendly interfaces and affordable prices. For connecting to the Internet, most of these devices make use of IEEE 802.11 wireless technology, commonly known as Wi-Fi, in addition to 3G/4G, due to Wi-Fi's speed, maturity, efficiency, and attractive pricing.

Given this rising demand, Wi-Fi is facing mounting issues of spectrum efficiency due to its utilisation of non-licensed frequency bands, so improvements continue to be added to the standards in order to improve performance and adapt it to new demands. For example, as Wi-Fi saturation increases in areas such as business centres, malls, campuses or even whole European cities, interference between these competing Access Points (APs) can begin to negatively impact users' experiences. At the same time, real-time interactive services such as Voice over IP, video conferencing, and online games, have grown in popularity and are now used across a range of mobile devices. These share the same connection with "traditional" applications, such as e-mail and Web browsing, but are far more bandwidth-intensive and require consistent network capacity to meet user Quality of Experience (QoE) demands.

In this context, the Horizon 2020 Wi-5 (What to do With the Wi-Fi Wild West) project proposes an architecture based on an integrated and coordinated set of smart solutions able to efficiently reduce interference between neighbouring APs and provide optimised connectivity for new and emerging services. Cooperating mechanisms will be integrated into Wi-Fi equipment at different layers of the protocol stack with the aim of meeting a demanding set of goals:

- Support seamless handover to improve user experience with real-time interactive services.
- Develop new business models to optimise available Wi-Fi spectrum in urban areas, public spaces, and offices.
- Integrate novel smart functionalities into APs to address radio spectrum congestion and current usage inefficiency, thus increasing global throughput and achieving energy savings.

## 1.2 Scope and structure of this deliverable

This deliverable expands on the use cases most relevant to Wi-5 as presented in D2.3 [1], and answers two research questions:

1) Would a solution such as Wi-5 fit into the roadmaps that operators and vendors are currently using for their Wi-Fi deployment?
2) Can we quantify the effect that the Wi-5 solutions would have on the actual performance of Wi-Fi systems as deployed in the current use cases?

The use cases presented in [1] focus on a selected set of scenarios. The choice of these scenarios was based on a thorough analysis of on-going work in the IEEE and Wi-Fi Alliance to identify the most pressing usage models, as well as the interests of the project partners and the members of the Operator Board. These use cases can be summarised as follows:

- **Airport/Train Station**: This use case focuses on the deployment and utilisation of large Wi-Fi networks in public areas, where the users are characterised by nomadic and there is a need to support the use of real-time applications.
- **Dense Apartment Building**: This use case focuses on the dense and uncoordinated deployment, operation and utilisation of Wi-Fi APs. This deployment scenario is characterised by radio interference between Wi-Fi APs and a lack of coordinated control over the wireless networks.
- **Pico-cell Street Deployment**: In this use case, we consider outdoor users initially connected to a cellular network and then switched to a Wi-Fi network that has been deployed by the mobile operator to off-load data.
- **Large Home/SOHO**: This represents a common scenario where the usual single AP deployment within a large home or office is extended to provide extra coverage and improve the user's QoE.
- **Community Wi-Fi Network**: This use case focuses on an emerging service where the network operators offer Wi-Fi network access to their on-the-go subscribers through existing residential and SME Wi-Fi infrastructure.

In this deliverable we answer research question 1) by means of an analysis of the roadmap of IEEE802.11, as presented in section 2, and a survey we conducted among six European operators, of which we present the results in section 3. Research question 2) is answered by the quantitative modelling of the dense apartment deployment use case regarding various spectral efficiency performance indicators, such as throughput per link, throughput per AP, and throughput per unit of volume. The results of this modelling work are described in section 4. Section 5 concludes this deliverable.

## 1.3 Relationship with other deliverables

The material in this document relates to the following deliverables:

D2.3: This presents the collected Wi-5 use cases and the requirements. Use cases can only be realistic when they are based on viable business models. Requirements follow from the concerns of all stakeholders playing a role in the business models.

D4.2 [2]: This deliverable, "Specification of Cooperative Access Points Functionalities version 2", describes a framework for the efficient exploitation of the radio resource, reducing interference between neighbouring APs and providing optimised connectivity for each user/flow that is served by an AP. It implements a fine-grained Radio Resource Management (RRM) algorithm to address interference in Wi-Fi networks by combining both channel assignment and transmit power adjustment techniques, and defines an enhanced AP allocation algorithm that will assist users/flows in selecting the most suitable AP according to the application running on the station in terms of QoS requirements. In D2.2 we have applied these algorithms to the dense apartment building use case and evaluated the results.

# 2 IEEE 802.11 evolutionary roadmap

## 2.1 Overview of IEEE 802.11 versions

Today, IEEE 802.11 is the main standard for wireless local area networks (WLANs), and the main implementations of IEEE 802.11 currently on the market are known as Wi-Fi. As technologies have become cheaper and easier to setup in the past years, the need for broadband and Wi-Fi coverage has steeply increased, so too has the density of Wi-Fi APs being deployed, to the point that interference has become an issue, as illustrated in section 4. The necessities of this dynamic radio environment imply adjustments to the IEEE 802.11 standard, on physical parameters such as modulation, coding schemes and power. To that extent, the IEEE 802.11 standard has been redesigned and new techniques have been developed, in order to cope with the increasing demands of today's users.

In 1980, according to [3], the IEEE assigned the name 802 to one of its standardisation projects. In 1997, one of the project groups, namely 802.11, released the first specifications for WLAN. From that time onwards, many additions and improvements were published and Table 1 provides an overview of all existing 802.11 versions, their current status, as well as their main feature in the context of Wi-5.

**Table 1:** Overview of the IEEE 802.11 versions

| IEEE 802.11 version | What it provides | Status |
|---|---|---|
| **P802.11-1997** | Standard for Wireless LAN Medium Access Control MAC and Physical Layer PHY Specifications | Legacy |
| **P802.11-1999** | Standard for Wireless LAN Medium Access Control MAC and Physical Layer PHY Specifications | Legacy |
| **P802.11f-2003** | Inter-Access Point Protocol Across Distribution Systems Supporting IEEE 802.11 Operation | Standard is in use |
| **P802.11a-1999** | Higher Speed PHY Extension in the 5GHz Band | Standard is in use |
| **P802.11b-1999** | Higher Speed PHY Extension in the 2.4 GHz Band | Standard is in use |
| **P802.11d-2001** | Operation in Additional Regulatory Domains | |
| **P802.11g-2003** | Further Higher Data Rate Extension in the 2.4 GHz Band | Standard is in use |
| **P802.11h-2003** | Spectrum and Transmit Power Management Extensions in the 5 GHz Band in Europe | Standard is in use |
| **P802.11i-2004** | MAC Security Enhancements | Standard is in use |
| **P802.11j-2004** | 4.9 GHz-5 GHz Operation in Japan | Standard is in use |
| **P802.11e-2005** | MAC Enhancements QoS | Standard is in use |
| **P802.11k-2008** | Radio Resource Measurement | Standard is in use |
| **P802.11r-2008** | Fast roaming | Standard is in use |
| **P802.11y-2008** | 3650-3700MHz operation in USA | Standard is in use |
| **P802.11n-2009** | High throughput | Standard is in use |
| **P802.11w-2009** | Protected management frames | Standard is in use |
| **P802.11p-2010** | Wireless Access for the Vehicular Environment | Standard is in use |
| **P802.11z-2010** | Extensions to Direct link setup | Standard is in use |
| **P802.11v-2011** | Wireless network management | Standard is in use |
| **P802.11u-2011** | Interworking with external networks | Standard is in use |
| **P802.11s-2011** | Mesh networking | Standard is in use |
| **P802.11ae-2012** | Prioritization of management frames | Standard is in use |
| **P802.11aa-2012** | Video transport streams | Standard is in use |
| **P802.11ad-2012** | Very high throughput at 60GHz | Standard is in use |
| **P802.11ac-2013** | Very high throughput at 6GHz | Standard is in use |
| **P802.11af-2013** | TV white spaces | Standard is in use |
| **P802.11ah** | Sub-1GHz | Under development |
| **P802.11ai** | Fast initial link setup | Under development |
| **P802.11aj** | China millimeter wave | Under development |
| **P802.11aq** | Pre-association discovery | Under development |
| **P802.11ak** | General link | Under development |
| **P802.11ax** | High efficiency WLAN | Under development |
| **P802.11ay** | Next generation 60GHz | Under development |
| **P802.11az** | Next generation positioning | Under development |

Starting with the **P802.11-1997**, 802.11 became the standard for wireless local area networks. This initial specification of the standard included data rates of 1 or 2 Mb/s which were operated at 2.4 GHz.

As the versions evolved, it was decided to separate the work group into two, in accordance with the band of operation: 2.4 GHz and 5 GHz. **802.11-1999** stood as the basis for **802.11a-1999** and **802.11b-1999**, which operated at 5 GHz and 2.4 GHz respectively. The complimentary code keying (CCK) mode was introduced with **802.11b-1999** to support 11 Mb/s. Orthogonal frequency division multiplexing (OFDM) was used in **802.11a-1999** and supported bandwidths of up to 54 Mb/s.

The 2.4 GHz band has the advantage of a better range of operation over the 5 GHz band, as a result of the fact that at higher frequencies the waves attenuate faster. Also, due to the high cost of radio frequency (RF) implementation at that time, the 5 GHz band was not utilized fully. All of this led to further development of the 2.4 GHz band, as the demand for data was higher. The **802.11g-2003** standard adopted the same specifications of **802.11a-1999**, as far as the physical layer (PHY) and media access control (MAC) was concerned, with the aim to support data rates of 54 Mb/s in the 2.4 GHz band.

As higher demands of data rates became needed, the IEEE 802.11 approved the creation of work group **802.11n-2009** aiming to achieve data rates of 100 Mb/s at the MAC layer. This version makes use of multiple-input multiple-output (MIMO) techniques such as spatial-division multiplexing (SDM), space-time block coding (STBC) and transmit beamforming (TxBF). In 2009, P802.11n-2009 was accepted as a standard in use.

The very high throughput (VHT) group was working on the development of the **802.11ac-2008** and added a standard with the intent of bringing additional changes to the MIMO methods. We can distinguish among these downlink multi-user methods (MU-MIMO) which allowed for up 160 MHz bandwidths and a maximum of 8 streams.

## 2.2 Contention window

QoS requirements for IEEE 802.11 wireless networks are becoming more and more important as the density of AP deployment is constantly increasing. IEEE 802.11 MAC assigns different contention windows to two priority classes in order to provide service differentiation. In IEEE 802.11e, a priority based CSMA/CA scheme would provide differentiated services across several types of applications [4]. Also the IEEE 802.11e version used a new channel access function called Hybrid Coordination Function (HCF), which was designed to have contention based channel access also named Enhanced Distributed Chanel Access (EDCA) and a contention free channel access mechanism. Each of the four Access Categories of EDCA acts as an independent virtual MAC and performs the same DCF (Distributed Coordination Function), with different Contention Windows. In IEEE 802.11e, the increase in the CW (contention window) size after collision is exponential. The probability of further collision between the same stations is therefore greatly reduced.

## 2.3 Using directional antennas and beamforming

Directional antennas are often called beam antennas. The idea behind a directional antenna is that it emits and receives greater power in a specific direction allowing for increased performance and reduced interference. Antennas propagate the signal through the air in a particular pattern.

The typical antennas commonly included in IEEE 802.11 products are omni-directional antennas that radiate signal in all directions around the antenna's axis. In the case of directional antennas, the transmission is focused in a certain direction by narrowly radiating only in that direction.

In the case of IEEE 802.11a/b/g, the APs usually track which antenna receives the fewest errors, in order to use it for the next transmission. Starting with IEEE 802.11n, instead of choosing the best antenna, the APs transmit data streams through all antennas at once. Receivers then combine the streams in order to boost the total bandwidth. IEEE 802.11n devices thus make use of MIMO antennas in order to take advantage of each available channel. In general, MIMO capable devices are characterized by the number of transmit (M) and receive (N) antennas in use simultaneously. MIMO can also be used in an analogous way by IEEE 802.11n devices, increasing throughput and reach through redundant transmissions. Another feature employed by IEEE 802.11n is the bonding of two regular (20 MHz) IEEE 802.11a/b/g channels, into one double-wide (40 MHz) IEEE 802.11n channel to support higher-throughput.

However, perhaps the most interesting feature that was adopted with IEEE 802.11n is TxBF. Without beamforming, IEEE 802.11n antennas radiate the signal in all directions, just like the omni-directional antenna found on older IEEE 802.11a/b/g devices. With beamforming, the transmitter can adjust the signal sent from each individual MIMO antenna in order to improve reception. This way, the sender can direct and aim a particular transmission in the direction of the destined receiver. In order for TxBF to work, close coordination between the sender and the receiver needs to occur. As the specific method to be used for TxBF was only defined in the IEEE 802.11ac standard, this technology is not likely to work between IEEE 802.11n devices from different vendors.

[5] is one of the first performance studies to consider directional antenna environments in IEEE 802.11 networks. According to this study, about 60% of unnecessary blocking assessments occur when directional antennas are used in the IEEE 802.11 protocol. [6] provides a further performance analysis of beamforming in Wi-Fi APs. A comparison is made between a single AP making use of beamforming versus multiple low-cost omnidirectional APs. The results of the simulation show that given certain circumstances the beamforming AP outperforms the regular APs. Moreover, it was observed that when it comes to data downloading, data beamforming AP has generally performed better, while when it comes to data uploading, the multitude of regular APs have performed better.

Another interesting performance analysis of beamforming performance is made in [7]. The outdoor performance of IEEE 802.11 wireless networks needs enhancement here as the conditions are rather difficult. As beamforming is presented more and more as the technology to increase performance of future systems, the article studied the performance of adaptive antenna array beamforming in real life outdoor environments. The test results showed that beamforming improves the throughput rates by a factor of 2 to 4 in near-LOS (near line-of-sight) situations and by about 37% in NLOS (non-line-of-sight) situations. In the short range situations implying direct line-of-sight, the gains from beamforming are minimal.

## 2.4 MIMO (SU/MU-MIMO)

In [8], a subspace beamforming method that decomposes a MIMO channel into multiple pairs of sub-channels is presented. The idea of geometric mean decomposition (GMD) and maximum likelihood (ML) detection are used in the presented performance analysis. The proposed subspace GMD scheme only requires two layers of detection or decoding. The performance analysis also shows that subspace beamforming performs nearly as well as optimum GMD performance, and to within only a few dB of the Shannon bound. The decomposition of a MIMO channel into multiple pairs of sub-channels is done in order to avoid the complexity of join detection and/or latency of having too many SICs (successive interference cancellations). According to literature [9], IEEE 802.11n has made a huge leap as compared to the preceding versions in terms of data throughput thanks mainly to MIMO antennas and channel bonding. The added complexity however has made it difficult to select the proper transmission rate, as well as the MIMO transmission technique (e.g. Spatial Diversity or Spatial Multiplexing).

IEEE 802.11ac introduces the use of MU-MIMO. The difference between SU-MIMO and MU-MIMO is that MU-MIMO adds multiple access (multi-user) capabilities to SU-MIMO, as illustrated in Figure 1. According to [10], most of the studies of SU-MIMO (single user multiple input multiple output) and MU-MIMO (multiple user multiple input multiple output) rely on PHY layer only or MAC (medium access control) layer only simulations. [10] proposes a new approach to simulation based on both PHY and MAC layers. Such a simulation has been performed and outlines that MU-MIMO transmissions can yield less throughput gain and be less stable than SU-MIMO. This directly impacts real-time applications by means of increased jitter and higher packet loss for the use of MU-MIMO. The approach to simulations presented in [10] is based on a multi-user simulation platform containing all the PHY layer specification together with a specific MAC layer, working together.

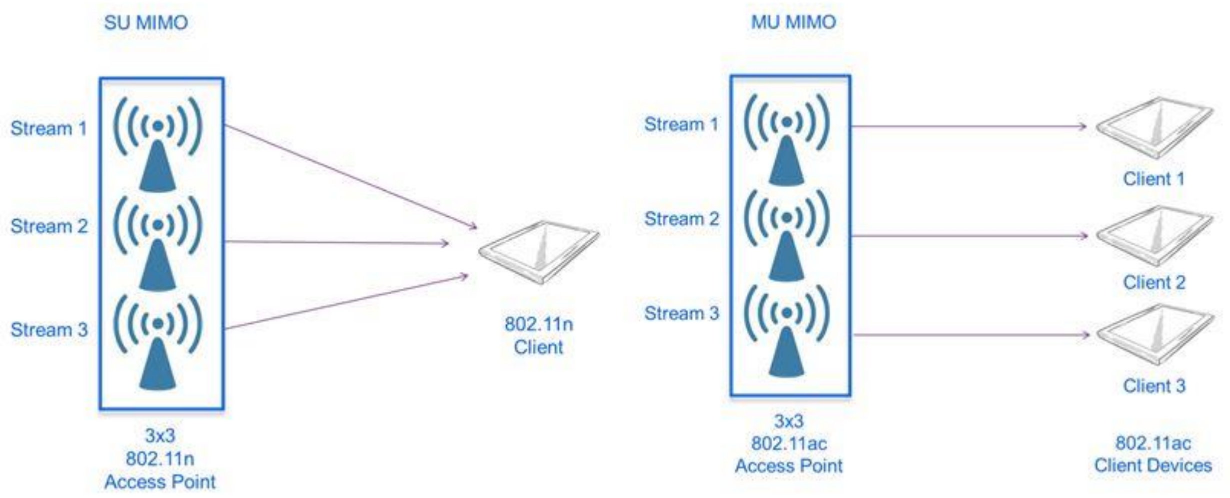


**Figure 1:** Differences between SU-MIMO and MU-MIMO

## 2.5 Adjusting power levels of Wi-Fi

The original purpose of IEEE 802.11h was the extension of WLAN operation in Europe to the 5 GHz band, where WLAN must coexist in a space already used for radar and satellite systems, by means of applying dynamic frequency selection (DFS) and transmit power control (TPC). This is the only application of TPC in current WLANs, and is only tuned to avoid WLANs interfering with radar and satellite.

In general one can, however, say that TPC has three critical purposes [11], namely:

1) an amelioration of the near-far problem (if all transmissions in a given area use the same power, then the ones closer will shadow the further ones),
2) a minimization of interference to and from other APs,
3) improving system performance on fading channels by compensating for fading dips.

Although until recently it was not considered possible to implement advanced power control techniques on off-the-shelf wireless devices. IEEE 802.11h was the starting point of innovation when it comes to TPC mechanisms, opening many new directions of evolution for IEEE 802.11 technologies [11]. The advantages of MIMO versions of IEEE 802.11 over single-input single-output (SISO) versions are also underlined by the TPC mechanism. The number of concurrent transmissions for the MIMO mode is reduced in comparison with SISO, and thus higher throughput and lower energy consumption is achieved.

Large scale 802.11 wireless networks also brought up the issue of spectral reuse and TPC was identified as being one of the most efficient ways to tackles this problem. For a long time, the assumption of using minimum transmit power has held, but falling into the hidden nodes (HN) problems has steered TPC mechanism advancements in seeking other TPC algorithms like the ones described in [12] and [13]. There needs to be a trade-off between the scalability of the network capacity and the creation of HN. In [13] this is achieved by reducing the transmit power on EN (exposed nodes), in accordance with specific algorithms, so that the effect of the creation of HN is avoided.

## 2.6 Seamless handovers

As Wi-Fi technology became more and more popular, the demands and use have become more formidable. In houses and bigger apartments, the model of a single AP is not viable because of the limited range of the signal. Wi-Fi range extenders have made an appearance as a solution to the above mentioned problem, but a new problem then arose as switching from the home network to the extenders network required wireless rebinding. The need of automatically swapping between the two networks without disruptions arose.

In Wi-Fi networks this concept is widely adopted and used in enterprise networks. Most of them are proprietary, but based on the IEEE 802.11r standard for fast roaming which targets a 50ms handover. As technology has evolved, the requirements for handovers and roaming between APs have become stricter. In this light, three types of handover can be distinguished:

- Fast handover – concerned primarily with the latency with no interest in packet loss aspect;
- Smooth handover – concerned with minimizing packet loss with no interest in the delays incurred;
- Seamless handovers – concerned with both latency and packet loss aiming to provide mobility while keeping the same QoS characteristics.

The SSID is a case sensitive, unique identifier formed of 32 alphanumeric characters and is attached to the header of packets transmitted using the IEEE 802.11 standards. Starting with IEEE 802.11f, an Inter-Access Point Protocol was developed in order to provide range extension for 802.11 networks, using virtual SSIDs. Virtual SSID were introduced with the idea of having multiple logical networks on the same physical AP(s). This idea also aided in tackling with the problem of seamless handovers, as the range of Wi-Fi networks is low and the performance losses in terms of latency, packet loss and QoS were diminished.

## 2.7 Wi-Fi standards in other frequency bands

There are versions of the IEEE 802.11 standard which are designed around using frequency bands other than the unregulated 2.4 and 5 GHz bands. According to [14], the benefit of using bands other than 2.4 and 5 GHz is that there are no previous WLAN technologies using them and therefore, there is no need for backwards compatibility and support. This means that the technologies that are developed within standards which operate in other frequencies can design the PHY and MAC protocol disregarding the previous legacy and use of inefficient methods and algorithms. Two defining versions of the IEEE 802.11 standards here are 802.11ah and 802.11ad.

The IEEE 802.11ah version focuses on the use of WLANs in sub 1 GHz frequency bands. The advantage of using the sub 1 GHz band is that the range of the AP is greatly increased as lower frequencies make this technically achievable. This is illustrated in Figure 2. The Wi-Fi Alliance has already introduced a certification for devices using IEEE 802.11ah, named Wi-Fi HaLow. The intended use for such devices would be in Smart Home environments, Smart City environments, automotive vehicle connectivity, as well as industrial, retail and agriculture deployments. One problem that arises with the use of sub 1 GHz bands however is that they are regulated, and usage is only allowed given low transmission powers. Another problem is that given the long range and high penetration capabilities through obstacles in the environment, the use of sub 1 GHz bands results in increased interference levels within environments with high densities of APs.

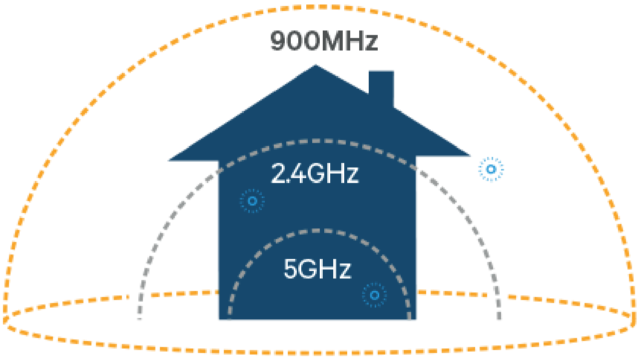


**Figure 2:** Range differences between Wi-Fi APs operating at different frequencies

The IEEE 802.11ad version is focused with achieving multi-gigabit per second data rates in wireless environments in the 60 GHz band. The Wi-Fi Alliance has promoted this version of the IEEE 802.11 standard under the name of WiGig. Even though the achievable throughputs are impressive (about 8 times the throughput of the latest versions of IEEE 802.11ac), the main disadvantage of using this version is that the 60 GHz signal is not able to penetrate walls at all. Despite this, current developments for this technology seek to provide a sufficiently strong signal in rooms other than where the AP is present through technologies like beamforming and taking advantage of the fact that the 60 GHz signal can propagate off reflections from walls and floors. However, the rate of development is slow compared to the current needs in congested environments. Another problem is that the developed solutions for wall penetration in the case of WiGig assume using lower operating frequencies (e.g. 2.4 or 5 GHz bands) and lower data rates. This makes 802.11ad part of the existent congestion problem rather than a solution to it.

## 2.8 Evolution of IEEE 802.11 standards in use

Given the developments as described in the previous subsections, we sketched the evolution from the original version of 802.11 through to the present in terms of throughput and frequency used. The result is shown in Figure 3.

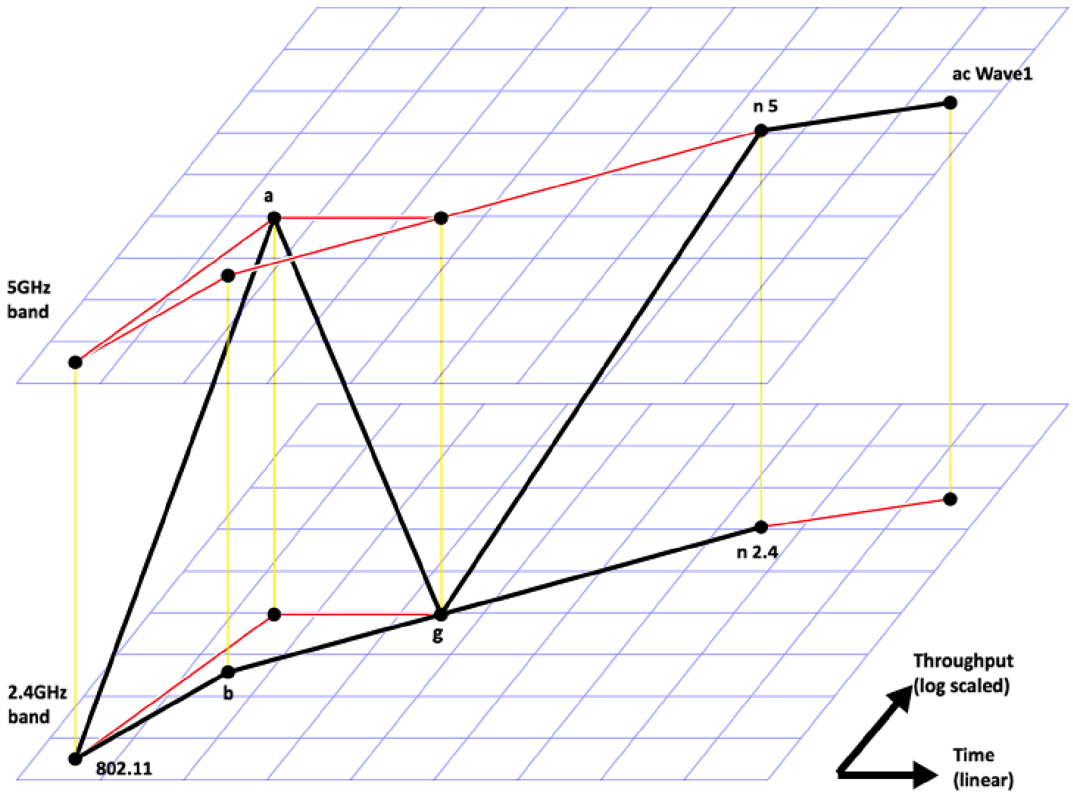


**Figure 3:** Evolution of the IEEE 802.11 versions of the standard over time underlining the throughput increases and frequency bands used. The x-axis runs from 1997-2013, whereas the y-axis runs from 2 Mb/s to 20 Gb/s. The black line shows how systems have evolved over time to higher throughputs, via 2.4 GHz-only systems (bottom black line), or including 5 GHz systems (top black line). The red and yellow lines are merely guidelines for the eye.

This figure shows that both the 2.4 and 5 GHz bands are of great importance from the perspective of the IEEE 802.11 standard. Even though the presence of problems in the 5 GHz band is due to another reason today (the use of only non – DFS channels), in the future congestion will eventually reach all the existent channels in the 5 GHz band and the situation will reach the congestion levels present in the 2.4 GHz band. This means that the congestion problem can be solved in the short-term by usage of all the available channels in the 5 GHz band, but in the long term a solution like the Wi-5 proposed mechanism is required to have the legacy systems still achieving the desired performance.

# 3 Operator's view on future Wi-Fi deployment

## 3.1 Questionnaire scope and response

Section 2 of this deliverable mainly describes the Wi-Fi vendors' view on future Wi-Fi development. Section 4 gives a quantitative example of the users' need of Wi-5 solutions given the current Wi-Fi deployment. Deliverables D2.1 [15] and D2.6 [16] show that viable business models exist for successful deployment of Wi-5. What is still missing in order to answer the question if Wi-5 solutions can indeed be deployed is an analysis of how well Wi-5 solutions fit into the current deployment plans of Wi-Fi operators. Operators have the largest influence when it comes to finding solutions to current existing problems as they are the effective owners of the majority of residential Wi-Fi deployments. To answer that question we first need to know what the operators' current deployment plans are, and to understand the context of these plans in terms of 1) the details of the existing deployments in the field, including their costs of maintenance and service (i.e. where is the operator coming from), and 2) the trends that are dictating the evolution of these deployments (i.e. what drives the operators' choices for the future).

To obtain this information, we composed and sent a questionnaire to 20 network operators. A questionnaire can provide specific inputs that are easy to categorize, interpret and analyse, while not taking too much of the respondent's time. Overall results are fed back to the participants in an anonymized way, increasing their awareness on the type and spread of the Wi-Fi issues.

The questionnaire was initially sent only to Wi-5's Operators Board. There are 14 network operators that form the project's first ring of dissemination partners, called the Operators Board (see http://www.wi5.eu/?page_id=193). Their role is to advise on the solutions developed by the project's consortium and feedback on the direction and scope of the work, leading towards solutions that fit the problems they are faced with. Besides the Operators Board, TNO is supporting an information exchange group of CTOs (chief technical officers) of small to medium sized European operators, interested in solutions for in-home problems for their clients (Wi-Fi performance being one of them). The questionnaire was also sent to 5 operators belonging to this group. Additionally, the survey was sent to the IT department of TNO's office in The Hague as, from a Wi-5 standpoint, they are also an operator.

A transcript of the questionnaire can be found in Annex A. It first states various questions on the details of the current deployments (what technologies, how many customers, which services and use cases are supported, etc.), after which it asks for details about maintenance (which issues, how are they currently solved, what does it cost, etc.). It then finishes with a number of questions on how the operators want to solve these issues in the future with the introduction of new technology and the promotion of standardisation.

Six operators from both the Wi-5 Operators Board and the CTO information exchange group have answered the survey. The size of the operators who have answered the questionnaire, as measured in the number of their customers which make use of their broadband services, is shown in Figure 4. While not all customers make use of a Wi-Fi service, it can be safely assumed that the number of Wi-Fi users is roughly proportional to the total number of customers.

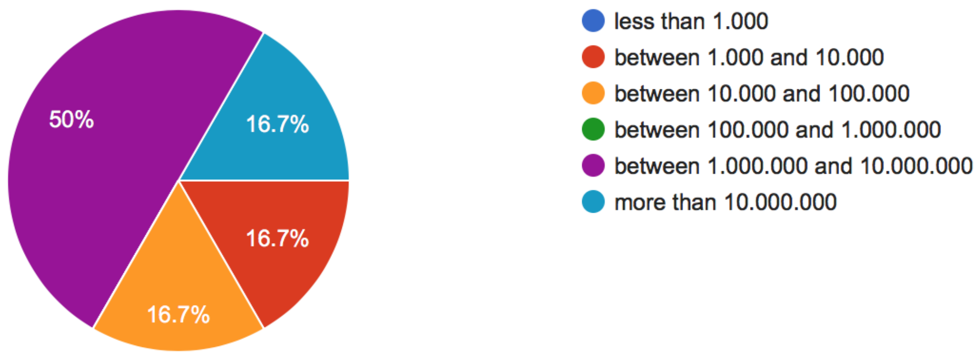


**Figure 4:** Size of responding operators in number of clients

## 3.2 Operator view on Wi-Fi technology aspects

Figure 5 shows how widely deployed each of the Wi-Fi versions as described by the IEEE 802.11 standards is. The most common versions that have been the major standards in use in IEEE 802.11 networks are: **b, a, g, n, ac**. Keeping in mind that as of the time of writing, versions IEEE 802.11b and IEEE 802.11a are now considered to be legacy, but they were still included in the survey in order to see how many of the operators still have legacy infrastructure.

To analyse possible differences between large operators and very large operators, the results of the questionnaire are also presented from the perspective of these significant subcategories of operators:

- **All operators** (includes the answers of all operators who have answered the questionnaire; this category includes the answers from both the next two subcategories);
- **Operators with more than 1M (one million) clients** (includes the answers of all operators above 1M clients whom have answered the questionnaire; this subcategory includes the answers from the next subcategory as well);
- **Operators with more than 10M (ten million) clients** (includes the answers of all operators above 10M clients whom have answered the questionnaire).

The subsets of operators above 1M and 10M clients are important as the averaged result of all the operators which have responded to this survey is not weighted. Therefore, the values can be misleading without gathering more respondent data. By showing all these 3 different mixes of data sets, a clearer depiction of the actual situation can be presented with regards to the situations for large (e.g. national operators from smaller European countries like Hungary, Austria, Denmark, etc.) and the very large operators (e.g. DT, BT, Telefonica, Orange, etc.).

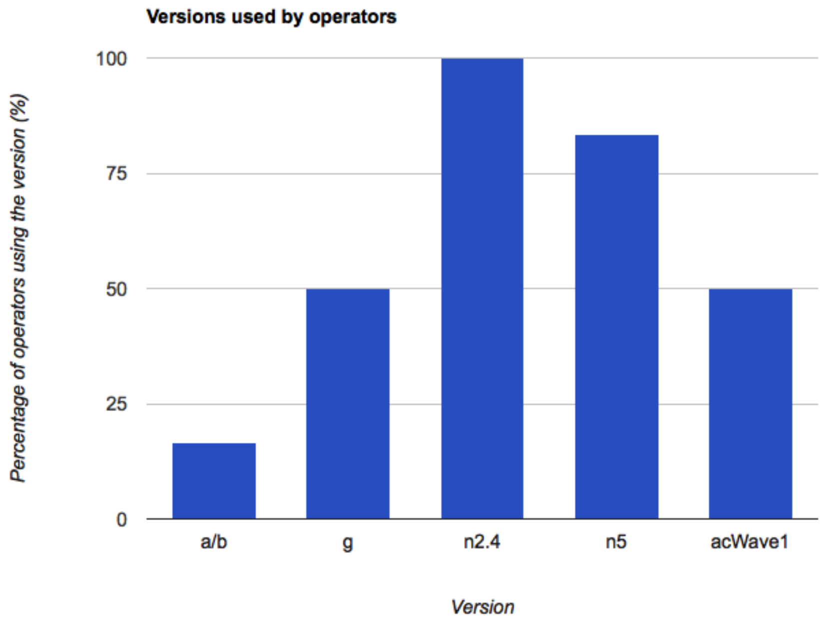


**Figure 5:** Percentage of operators using each of the Wi-Fi versions

The operators were also asked to provide the exact distribution of the deployment of Wi-Fi versions among their customers. The results to this question are shown in Figure 6. To clarify the information presented in Figure 6: Versions distribution among operator categories the exact data values are presented in Table 2.

**Table 2:** Exact values of versions distribution among operator categories

| Version | a/b | g | n 2.4 | n 5 | ac Wave 1 |
|---|---|---|---|---|---|
| **All operators** | 1.63% | 13.58% | 40.20% | 29.36% | 15.21% |
| **Operators above 1M** | 0.64% | 6.83% | 55.32% | 30.18% | 7.01% |
| **Operators above 10M** | 2.56% | 17.94% | 38.46% | 28.20% | 12.82% |

From table we can conclude the following:

- Versions **a/b** are now legacy, as the number of deployments that still use these versions is limited and the versions are the oldest still in use;
- Version **g** is at the end of its life cycle, as the popularity of this version among deployments is low and it is one of the oldest versions still in use;
- Version **n** is at the middle of its life cycle amounting for most of the deployments in both **2.4** and **5** GHz bands (considering that in the 2.4 GHz band, only b, g, and n 2.4 versions are used and in the 5 GHz band, only a, n 5, and ac versions are used), also considering that is one of the more recent versions;
- Version **ac** is at the beginning of the life cycle, seeing a low amount of popularity among operator deployments and being one of the latest technologies available (ac Wave 2 devices have just hit the market, but are not present yet in operator deployments).

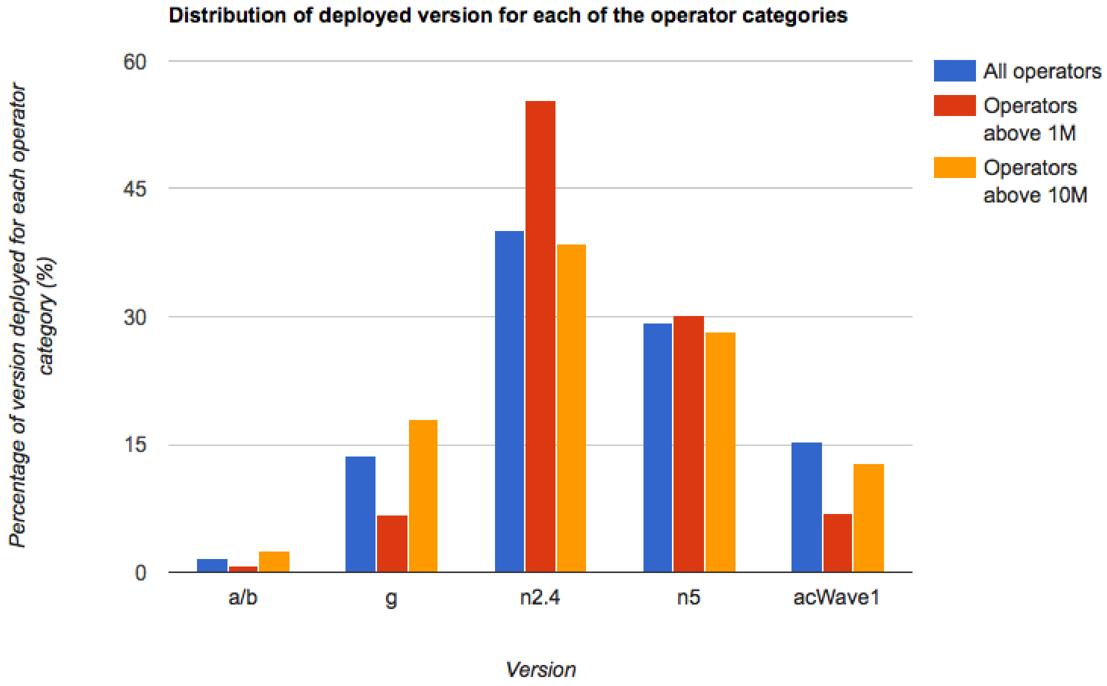


**Figure 6:** Versions distribution among operator categories

As it is important to determine the correct circumstances in which operators have their deployments, the survey offered the responders the opportunity to characterize the situation of their deployments by choosing a percentage of the five use cases identified as most relevant by the Wi-5 project in [1]. The operators which have replied to this questionnaire, had the opportunity to add their own use cases and the only additional one they have chosen to add was: Enterprise networking. The responses are also shown in Table 3 and Figure 7. Out of these, the dense apartment building stands out as being very important for all considered subsets of operators.

**Table 3:** Use case relevance

| Use case | All Operators | Operators above 1M | Operators above 10M |
|---|---|---|---|
| Airport / train station | 33.33% | 22.75% | 6.67% |
| **Apartment building** | **31.70%** | **37.96%** | **33.33%** |
| Pico-cell street deployment | 6.50% | 5.31% | 6.67% |
| Large home / SOHO | 13.00% | 17.01% | 33.33% |
| Community Wi-Fi | 6.50% | 5% | 20% |
| Other (Enterprise) | 8.94% | 11.95% | 0% |

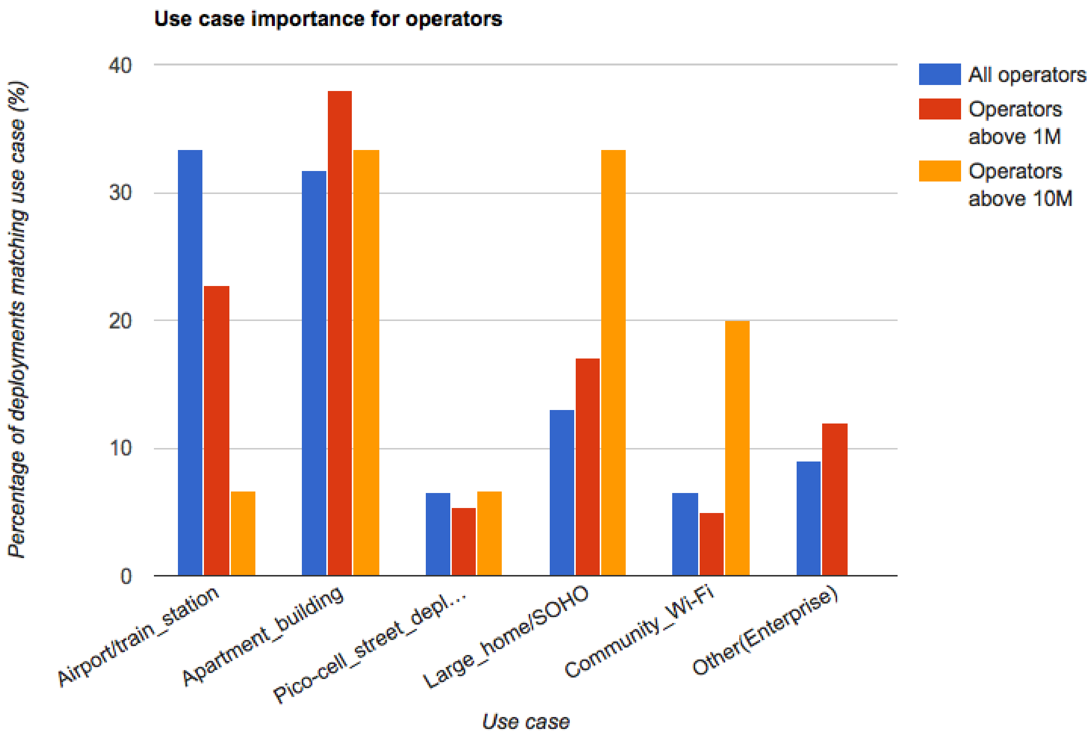


**Figure 7:** Relevance of the Wi-5 use cases to the responding operators

In order to establish the current problems that the operators are being faced with when it comes to their Wi-Fi deployments, we next analysed the amount of technology-related customer complaints the operators receive per year. The results are depicted in Figure 8, and show a direct correlation between their size and the number of technically related complaints received: with most operators this amounts to 1-10% of their total customer base. Of these complaints, the answers on question 9 of the questionnaire reveal (not graphically depicted) that out of all the customers that report a technical problem to their operator within a year, on average ~25% reports a Wi-Fi related problem. This is quite significant and would translate to hundreds of thousands of help desk calls per operator per year.

The questionnaire further tries to establish the nature of the Wi-Fi related problems into the following categories:

- No connectivity (no uptime since problem encountered);
- Poor connectivity (some uptime since problem encountered);
- Poor service performance (100% uptime; throughput problem).

The results are shown in Figure 9. As Wi-5 is trying to solve congestion issues in densely populated areas, and Wi-Fi congestion is an inherently stochastic phenomenon, it will not solve the “no connectivity” category of issues. However, it is expected to have a significant impact on the other sub-categories, which together make up for more than 60% of the Wi-Fi related help desk calls.

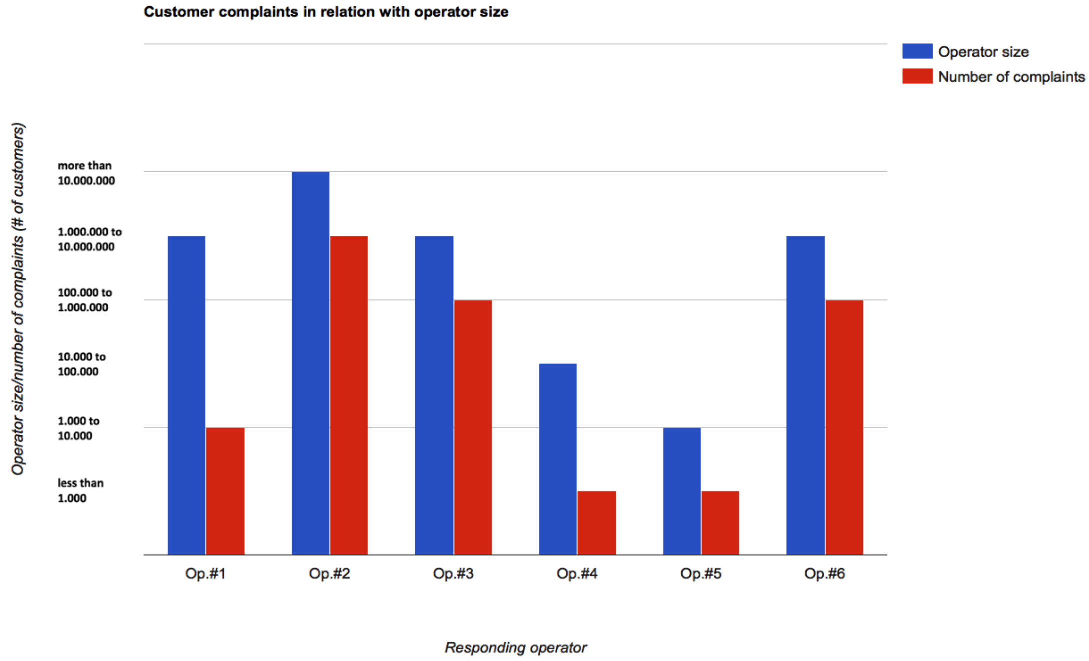


**Figure 8:** Relation between operator size and complaints received (in # of customers)

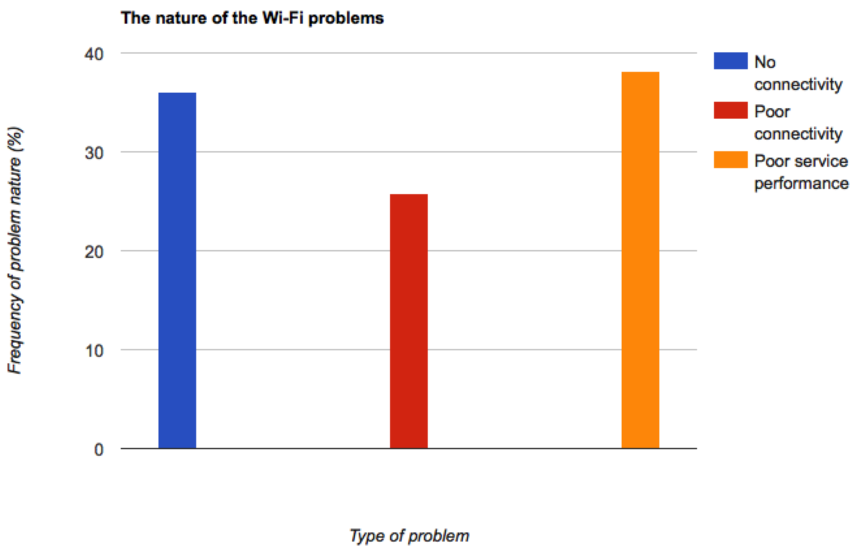


**Figure 9:** The nature of Wi-Fi problems

## 3.3 Operator view on Wi-Fi business aspects

The second part of the survey focuses on the current business aspects associated with the solutions adopted to solve the Wi-Fi related problems. First of all, the questionnaire tries to establish the costs for handling Wi-Fi related problems. Afterwards it looks into the costs associated with escalations of the problems which lead to on-site assistance. Such escalations appear to occur fairly often. The questionnaire also tries to find out how often the Wi-Fi problems can be solved remotely, and how often they are related to another misconfiguration. The results are shown in Table 4: Business aspects of the survey.

**Table 4:** Business aspects of the survey

| | All operators |
|---|---|
| **Average cost of solving Wi-Fi problems** | **€11,52** |
| **Average cost of Wi-Fi on-site assistance** | **€42,58** |
| Escalation to on-site assistance | 18.35% |
| Frequency of remote assistance | 45.81% |
| Frequency of being related to another misconfiguration | 15.85% |

Regarding the operators' future plans of changing the current version of the Wi-Fi service provided, 90% of the operators intend to change it. As shown by the answers of the questionnaire, the most feasible version to change to for operators is IEEE 802.11n and the reasons for doing this are:

- compatibility with both 2.4 and 5 GHz bands
- increased performance for their customers
- (perceived) suitability of this version to high density deployment areas.

The answers on the final (open) question in the questionnaire can aggregated as follows:

- All of the operators find it important that the methods for the detection and solving of their existing Wi-Fi problems is well supported and agreed upon by industry and customers.
- Most of them agree with the idea of mutual collaboration and Wi-Fi management in areas with high densities of APs.

Overall, we can conclude that by and large the operators intend to keep following the Wi-Fi Alliance product roadmap with regard to their Wi-Fi deployment plans, given the needs of their customers. It can therefore be safely stated that the operators' Wi-Fi roadmap is just an extension of the IEEE 802.11 technology roadmap as presented in section 2.

We can also conclude that the answer to the research question "Would a solution such as Wi-5 fit into the roadmaps that operators and vendors are currently using for their Wi-Fi deployment?" is "yes":

- Deliverables D2.1 [15] and D2.6 [16] show that viable business models exist for successful deployment of Wi-5.
- Even though most of the operators consider the 5 GHz band as a solution to the current congestion in the 2.4 GHz band, they also welcome the idea of managing the existing 2.4 GHz Wi-Fi environment better than what is done today. The latter is what Wi-5 is promising to deliver.
- It is important that Wi-5-like solutions become part of the IEEE 802.11 and Wi-Fi Alliance roadmap. This is not an unreasonable assumption, as management solutions (e.g. 802.11k) are already part of their roadmap, and also SDN is already well accepted by the industry, but requires effort from the industry partners affiliated to the project.

# 4 Quantitative modelling of the dense apartment block deployment use case

## 4.1 The Wi-Fi jungle

This section focuses on the question if we can quantify the effect that the Wi-5 solutions have on the actual performance of Wi-Fi systems as used in the current use cases. In section 3, we showed that the responding operators with over 1M clients agreed that the dense apartment block use case is the most relevant for them, as listed in Table 3. In D2.6 [16] we showed that this use case is arguably also the most challenging one. The overwhelming success of tablets, smart phones, and other personal networked devices is a key factor driving the dense deployment of Wi-Fi APs in practically all homes that are connected to the Internet.

The drawback of this dense deployment is the increased potential for co-channel and adjacent-channel interference of nearby Wi-Fi devices. Wi-Fi, as with most other technologies used in unlicensed bands, does not include mature radio resource management protocols to optimize use of the frequency spectrum in systems consisting of a large number of uncoordinated APs, such as apartment blocks. Figure 10 shows a typical example of the resulting signal strengths from different APs observed by a wireless device operating in the 2.4 GHz band in a densely populated residential area. This is the so-called the Wi-Fi Jungle (see e.g. http://www.viichi.org/index.php/wifi-ally-app).

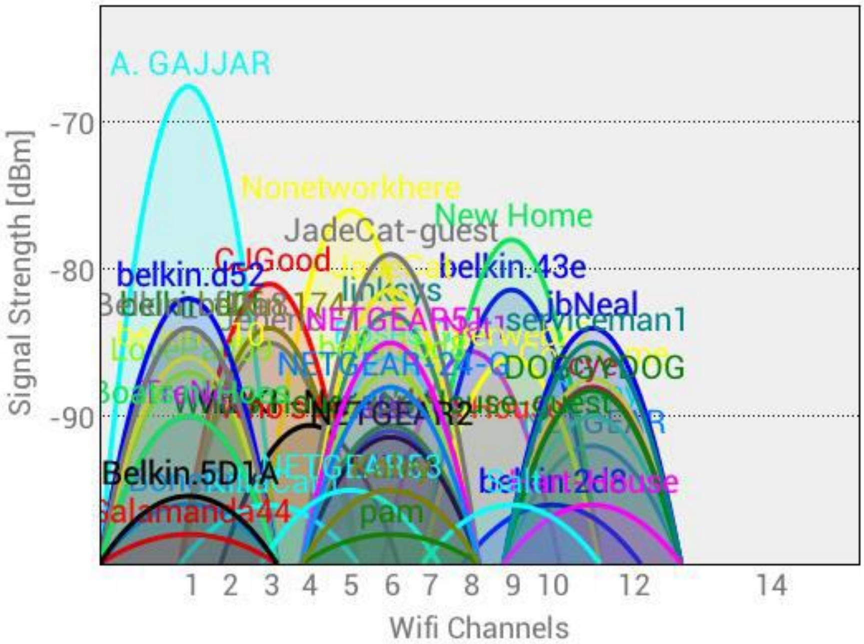


**Figure 10:** A typical example of signal strengths from different APs observed by a wireless device operating in the 2.4 GHz band in a densely populated residential area

Although there is plenty of anecdotal evidence that many users are experiencing Wi-Fi congestion problems in dense apartment blocks, and suffer from serious performance degradation as a result, surprisingly little research has been done so far to quantify the pervasiveness and severity of the problem [17]. In [18], Ozyagci et al show that, in theory, the performance degradation due to Wi-Fi congestion can be so bad that the number of packet collisions becomes too large and the area throughput (the amount of useful bits per time unit successfully transmitted in a given area) goes down when more APs and devices are added (see Figure 11). This situation is called spectral over-congestion.

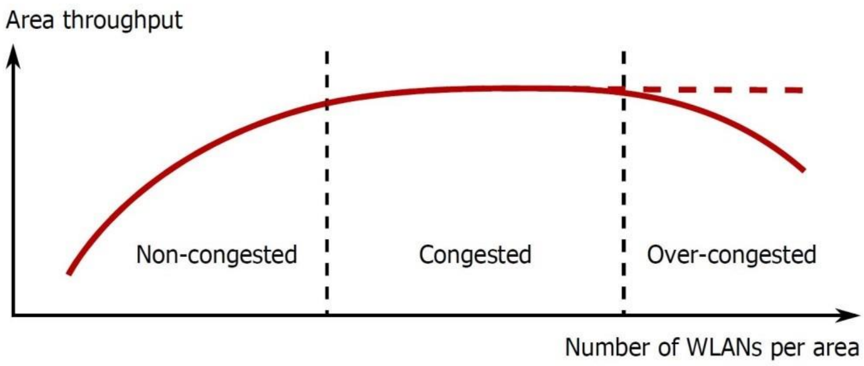


**Figure 11:** Decline of the area throughput due to spectral over-congestion [18]

It should also be noted that simply migrating to other (higher) frequencies may alleviate the problem for some time, but is not a satisfactory long-term solution. Besides the 2.4 GHz band, the authors have already observed congestion problems in the 5 GHz unlicensed band also. This is surprising, as this band has 21 non-overlapping 20 MHz wide channels (see Figure 12), i.e. 18 more than the 2.4 GHz band, and as shown in the previous section, 5 GHz is currently much less deployed than 2.4 GHz systems. However, as the 5 GHz band is also used for commercial, military and weather radar systems, the channels on which these radar systems work may only be used by Wi-Fi devices on the condition that they are immediately freed upon detection of these radar signals. Therefore, Wi-Fi devices operating at 5 GHz must have DFS mechanisms implemented as standardised in IEEE 802.11h.

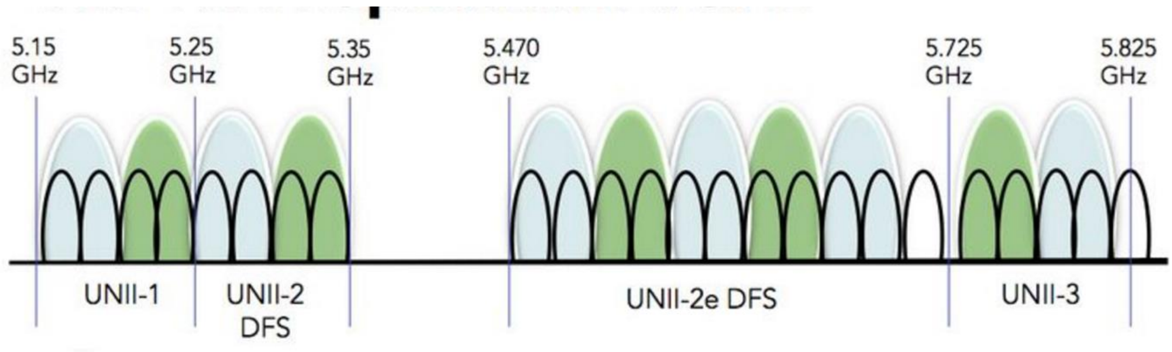


**Figure 12:** The 5 GHz unlicensed band with DFS and non-DFS channels

Though the 5 GHz unlicensed spectrum offers so many non-overlapping channels, most of the devices currently deployed are only capable of using the UNII-1 channels, because implementing DFS would increase the cost of the devices. As the UNII-1 band is nearly as narrow as the 2.4 GHz band, it is therefore not surprising that residents of high-density buildings already report congestion in the 5 GHz band. As further anecdotal evidence we provide a spectral scan of the 5 GHz band in Figure 13, as recently observed in the TNO offices in central The Hague, which are embedded in a high-rise building largely consisting of apartments. Here we see that indeed only the UNII-1 bands are used and at least 15 different APs are making simultaneous use of only 4 channels.

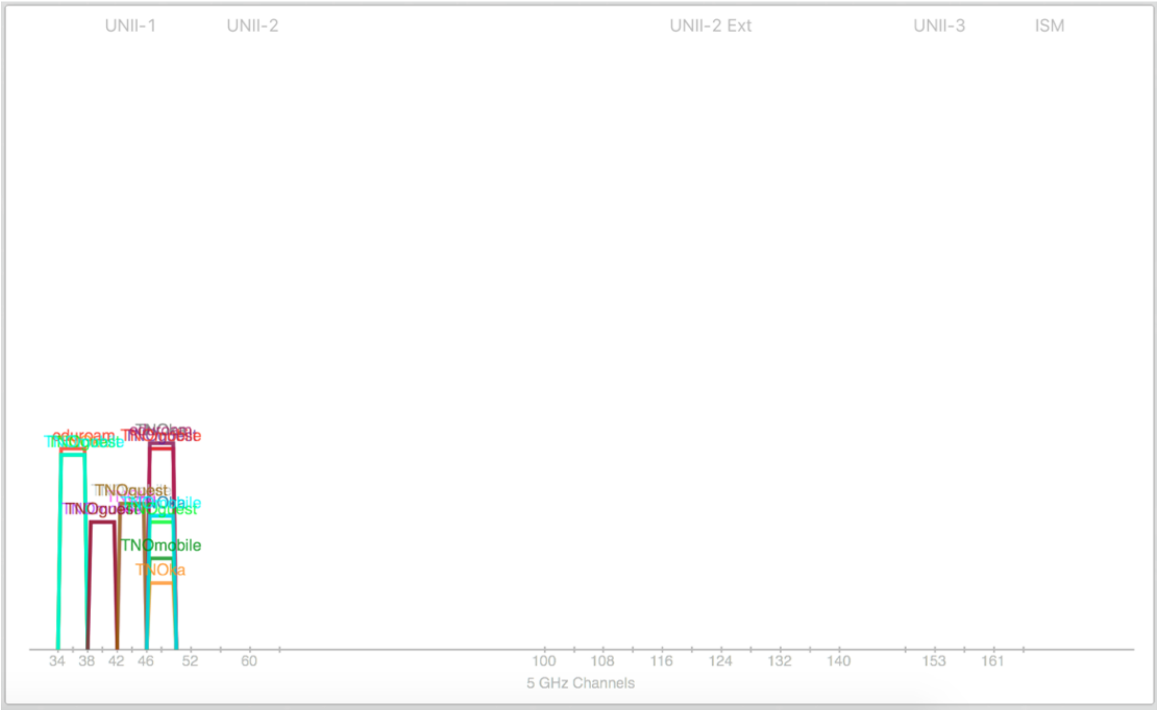


**Figure 13:** 5 GHz spectrum reading in the New Babylon office of TNO

In the remainder of this section we show a simulation of a realistic apartment block where over-congestion can indeed be a problem in real life. As far as we know, we are the first to model Wi-Fi performance in a realistic building and in 3D. We also show that collaboration between AP operators is needed to solve this problem.

## 4.2 Simulation set-up

In the modelling of the dense apartments block use case we took the apartment building “De Baron” in Zoetermeer, the Netherlands as an example (see Figure 14). The building has four floors, four wings and a total of 75 apartments. For the scope of the simulation, only one wing of the building is considered.


**Figure 14:** “De Baron” building and the floorplan of the selected wing

The floor plan is the same for all of the four floors and each floor is composed of four large apartments and one smaller studio (a total of five apartments per floor). The wireless APs are situated within the utility closets in each of the apartments.

We assume that there are a maximum of three devices actively using Wi-Fi at any given time in each of the large apartments (for instance one laptop, one tablet and one mobile phone), and two devices in the small studios. The model of the simulated scenario thus consists of 76 (19 per floor, 4 identical floors) active Wi-Fi devices in total being active in the building wing at the simulated moment. This could be, for instance, during an evening when users are at home and each of the devices is trying to do the following:

- All the laptops are used for video chat via Skype;
- All the tablets are used for watching video content offered by Netflix;
- All the phones are doing updates for their installed applications.

This scenario is depicted in Figure 15.

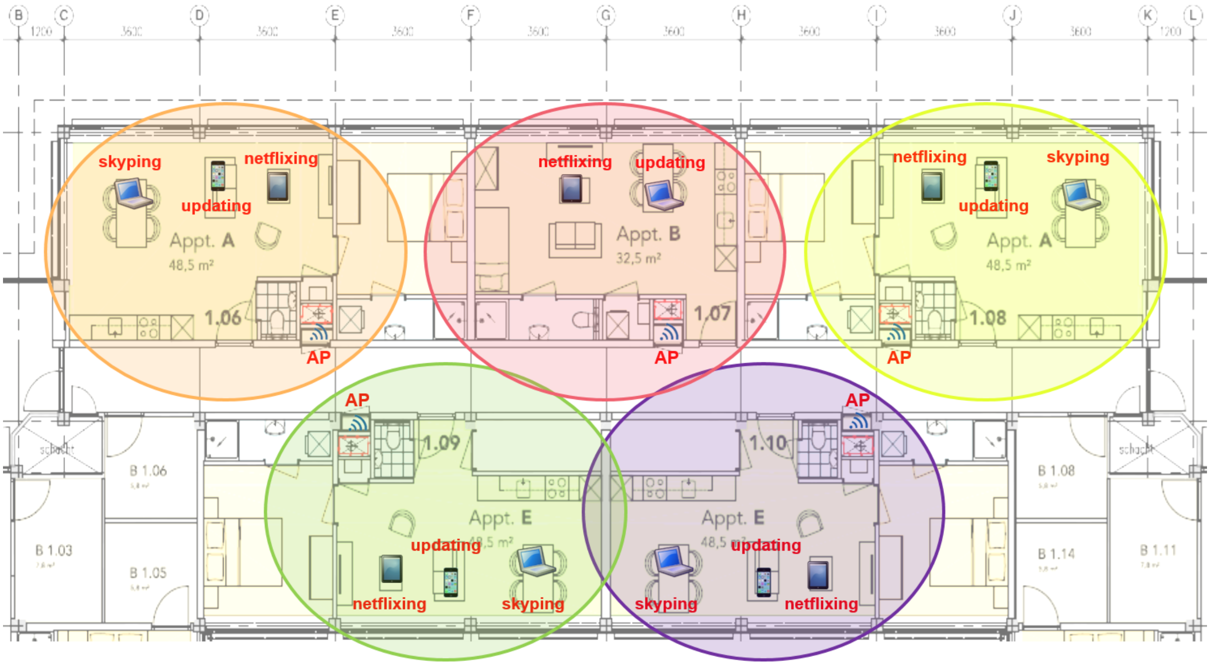


**Figure 15:** Usage scenario: many devices using Skype / Netflix / performing updates; Wi-Fi APs are in utility closets.

In order to obtain high fidelity results using realistic Wi-Fi network models, we use OPNET modeller 17.5 as a simulation tool. To model this scenario in OPNET the signal attenuation between each two of the 76 devices needs to be calculated. For this we used the following attenuation values for thick walls, thin walls, floors, and air, for perpendicular penetration, as taken from [19] and [20]:

- **Thick walls** – high density, of 22.5 cm thickness, surrounding each apartment: **18dB**;
- **Thin walls** – low density, of 11cm thickness, account for all apartment internal walls: **5.5dB**;
- **Floors** – high density, account for floors between the different levels of the wing: **25dB**;
- **Air** – accounts for the distances between the devices with no obstacles: **1dB/meter**.

This results in a 76x76 attenuation matrix which is used to define custom pipeline stages in OPNET. Non-perpendicular penetration is taken into account by measuring the thickness of the wall along the straight line between a transmitter and a receiver. The attenuation between two devices on different floors is also calculated based on the straight line between those devices (using Pythagoras): The vertical component of the attenuation consists of 2.6m of air and 0.5m of floor.

In OPNET, the model then looks as shown in Figure 16.

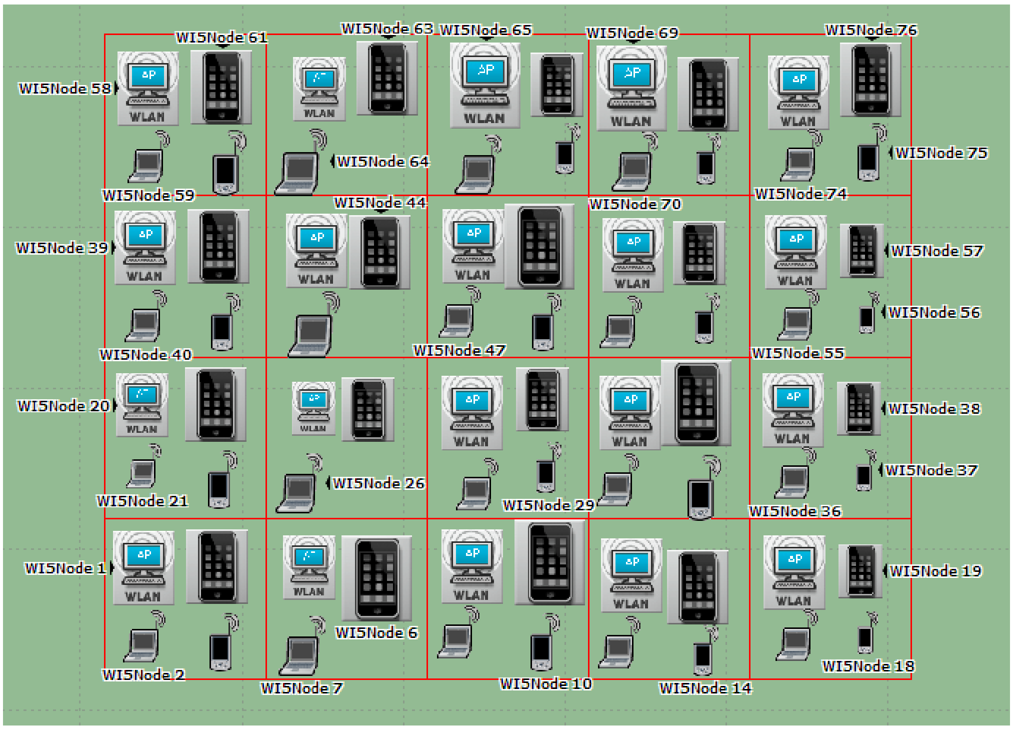


**Figure 16:** The OPNET model of the 76 Wi-Fi devices in the building wing

In this deliverable we only present simulation results for the 2.4 GHz band, assuming that everybody is using IEEE 802.11g, and sending a maximum amount of traffic from the AP to the devices. The only variable in the simulation is the channel selection. The transmission power is fixed at 100 mW. In future work we will also use other bands, Wi-Fi versions, and traffic patterns which better mimic the usage scenario presented before.

Traffic flows are generated according to a finite state machine using the following parameters:

| | |
|---|---|
| Start Time (seconds) | Exponential(0.01) for APs, Never for other devices |
| ON State Time (seconds) | Exponential(3) |
| OFF State Time (seconds) | Exponential(0.01) |
| Stop Time (seconds) | Never |

Within each traffic flow, the packets are generated according to the following parameters:

| | |
|---|---|
| Interarrival Time (seconds) | Exponential(0.00039) |
| Packet Size (bytes) | Constant(1024) |
| Segmentation Size (bytes) | No Segmentation |

This results in a traffic flow averaging 1024*8/0.00039 = 21 Mb/s.

Using maximum traffic assumes a worst case scenario, but it makes the results easier to compare with theory. The performance results are presented in a performance matrix, which maps to the different apartments as shown in Figure 17. The numbers represent whatever is calculated for a specific simulation, e.g. the average throughput per device per apartment (i.e. per AP) in Mb/s. The colour coding is a subjective index representing “good” (green), “fair” (yellow), or “bad” (red).

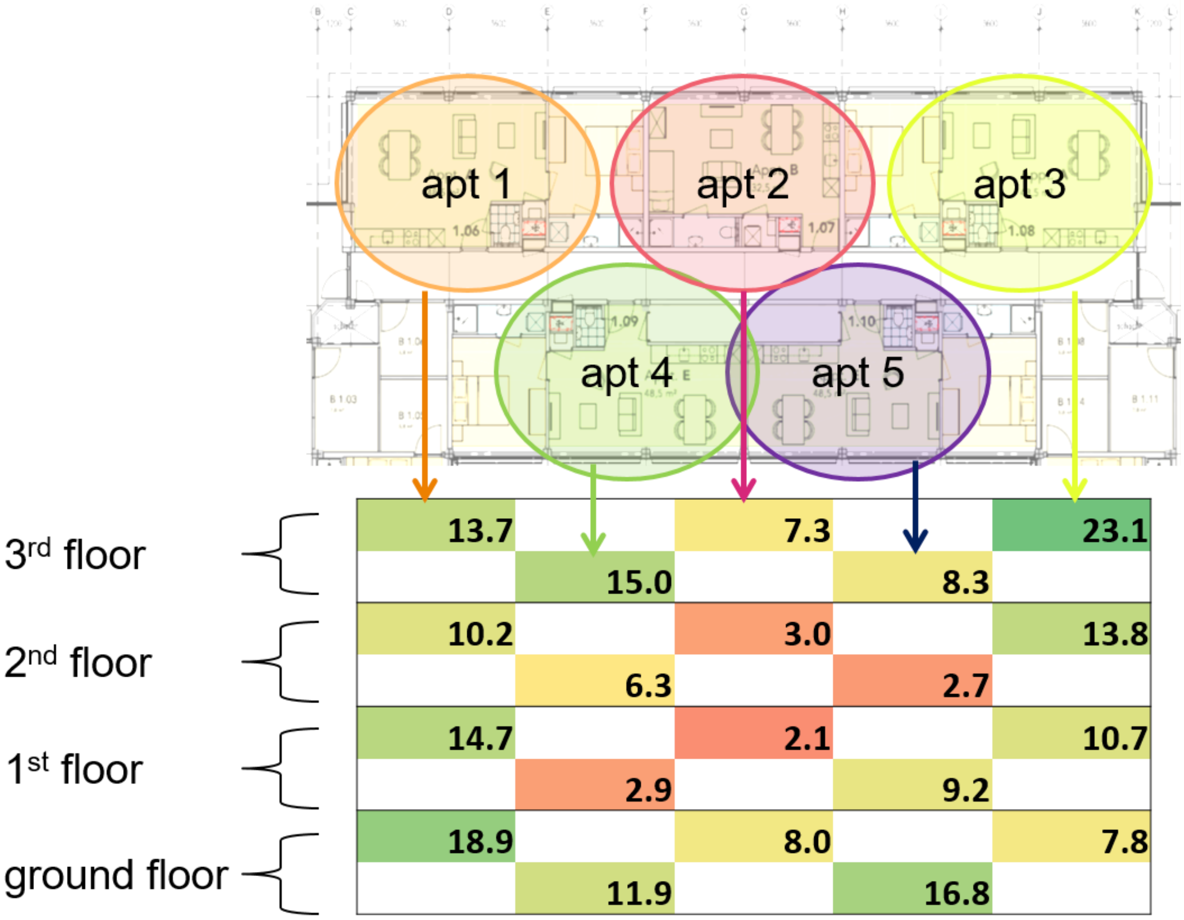


**Figure 17:** Example of a performance matrix resulting from a simulation

## 4.3 Simulation results without channel assignment

The goals of this experiment are:

- To show what performance people are experiencing today in a typical apartment block without any form of channel assignment
- To create a baseline to which our results with channel assignment can be compared
- To validate our set up.

Next, we isolate the apartments by adding an additional box (wall, floor and ceiling) around each apartment. We then increase the attenuation losses caused by these additional walls from 0 dB (this is the original situation without the box as described in section 4.2 above) to 70 dB, in steps of 10 dB. All APs use channel 1. Traffic is broadcasted from the AP to the different devices in the apartment. Figure 18 shows the average throughput per apartment (in Mb/s).

**0 dB**

| | | | | |
|---|---|---|---|---|
| 2.63 | | 1.17 | | 2.65 |
| | 1.69 | | 1.86 | |
| 1.50 | | 0.88 | | 1.37 |
| | 1.12 | | 1.13 | |
| 1.52 | | 0.90 | | 1.36 |
| | 1.13 | | 1.15 | |
| 2.73 | | 1.27 | | 2.70 |
| | 1.75 | | 1.89 | |

**40 dB**

| | | | | |
|---|---|---|---|---|
| 9.5 | | 1.62 | | 9.78 |
| | 7.6 | | 6.89 | |
| 8.73 | | 0.82 | | 9.13 |
| | 6.16 | | 6.46 | |
| 8.62 | | 0.8 | | 9.14 |
| | 6.25 | | 6.45 | |
| 9.66 | | 1.6 | | 9.81 |
| | 7.53 | | 6.91 | |

**10 dB**

| | | | | |
|---|---|---|---|---|
| 5.55 | | 1.89 | | 5.53 |
| | 4.2 | | 4.24 | |
| 1.35 | | 0.24 | | 1.4 |
| | 0.96 | | 0.87 | |
| 1.35 | | 0.25 | | 1.42 |
| | 0.94 | | 0.86 | |
| 5.59 | | 1.87 | | 5.56 |
| | 4.23 | | 4.2 | |

**50 dB**

| | | | | |
|---|---|---|---|---|
| 6.7 | | 11.3 | | 6.96 |
| | 8.85 | | 8.76 | |
| 9.76 | | 8.69 | | 9.85 |
| | 6.23 | | 6.18 | |
| 10 | | 8.5 | | 9.88 |
| | 6.02 | | 6.25 | |
| 6.49 | | 11.5 | | 6.93 |
| | 9.05 | | 8.74 | |

**20 dB**

| | | | | |
|---|---|---|---|---|
| 4.8 | | 4.03 | | 7.38 |
| | 5.02 | | 3.26 | |
| 1.59 | | 1.59 | | 2.51 |
| | 1.95 | | 1.33 | |
| 1.6 | | 1.51 | | 2.51 |
| | 1.93 | | 1.31 | |
| 4.83 | | 4.03 | | 7.45 |
| | 5.03 | | 3.28 | |

**60 dB**

| | | | | |
|---|---|---|---|---|
| 11.3 | | 9.4 | | 11.2 |
| | 14 | | 14 | |
| 9.87 | | 10.3 | | 9.88 |
| | 6.84 | | 6.88 | |
| 9.74 | | 10.4 | | 9.73 |
| | 6.87 | | 6.82 | |
| 11.4 | | 9.26 | | 11.4 |
| | 14 | | 14 | |

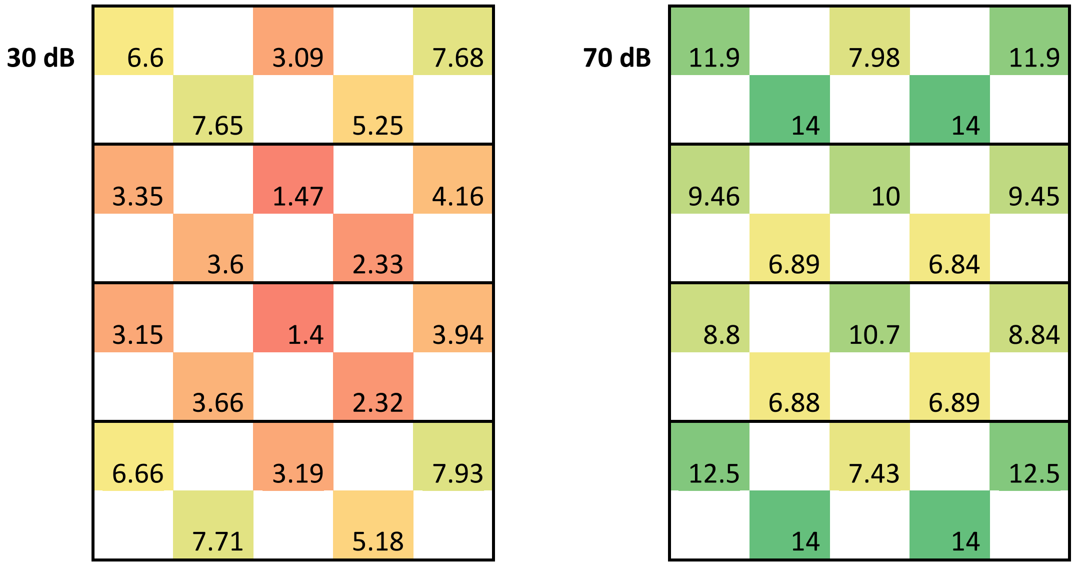


**Figure 18:** Average throughput per apartment for increasing isolation between the apartments when all APs function on channel 1. 0 dB represents the standard configuration as described in section 4.2.

The total average throughput (first averaged over all receiving devices in an apartment, and then averaged over all apartments) for increasing attenuation losses due to the additional isolation is shown in Figure 19.

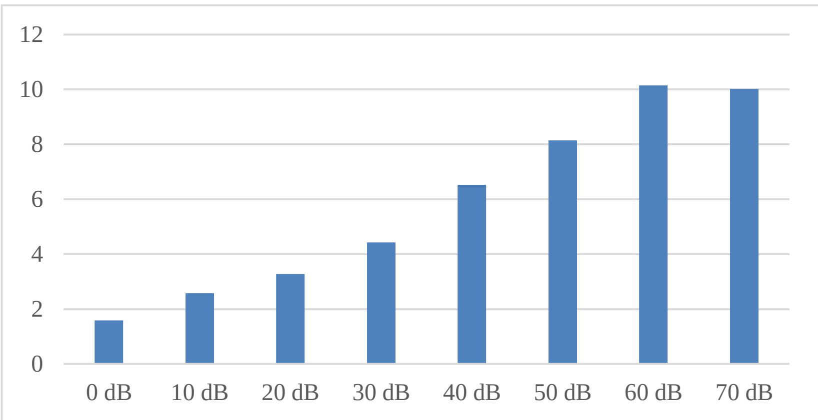


**Figure 19:** Average throughput over all apartments for additional walls with increasing attenuation, in Mb/s

From these experiments we can draw the following conclusions:

- In a normal apartment block, all apartments have their Wi-Fi only performing on ~5-10% of their maximum capacity if all APs operate on the same channel. This is a very low performance, and proves that over-congestion is indeed a problem in current deployments. Having all APs operating on the same channel 1 is not a typical use case, but neither is it unrealistic: many of the older APs have channel 1 configured as their default and have a very basic channel selection algorithm (if they have one at all), often converging to channel 1. Most people do not change the default settings of their AP.
- In most cases, the apartments in the middle of the block experience the worst performance. Only at attenuations >50dB some of the middle apartments seem to experience a somewhat

better performance than their direct neighbours. These apartments turn out to be the smaller ones of the 5 apartments that every floor contains, and have only 2 devices connected to their AP, at a relatively short distance and without any obstructions. They benefit first of the increase in isolation between the apartments, as inter-apartment interference is their only cause of performance decrease.

We also carried out a simulation with 100 dB attenuation between the apartments. The result is shown in Figure 20. With an attenuation loss of 100 dB between neighbouring apartments we achieve the throughputs we expect in a non-interference situation. Together with realistic outcomes shown in Figure 19, this experiment validates our simulations.

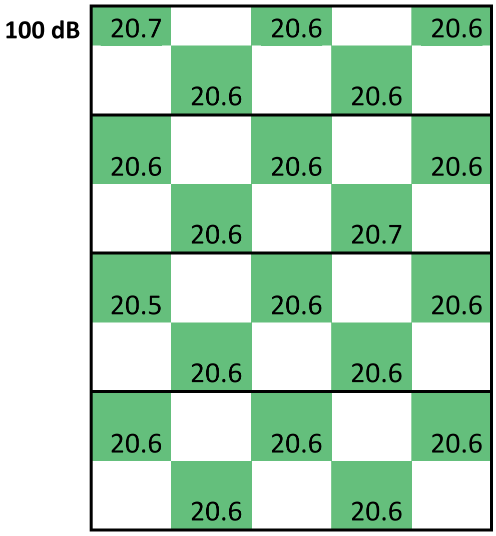


**Figure 20:** Average throughput per apartment when the apartments are fully isolated from each other

So even with an additional attenuation loss of 70 dB between neighbouring apartments, we observe slightly less than half the throughput of the non-interference case. This is caused by the instability that little disturbances can already cause on Wi-Fi connections.  This is shown in Figure 21, where we plot for 70dB attenuation the throughput-per-device over simulation time. We observe that while many Wi-Fi links show a stable performance, many others show a very unstable performance. It should be noted that Wi-Fi traffic is stochastic, not only because we set the traffic parameters as given in section 4.2, but also because the MAC layer includes random back-off mechanisms, etc. Therefore the interference that devices suffer from other Wi-Fi devices is stochastic too. For some devices this averages out, for others less so. The average throughput per device per AP are shown in Figure 18, and the total average throughput for the whole apartment block is shown in Figure 19.

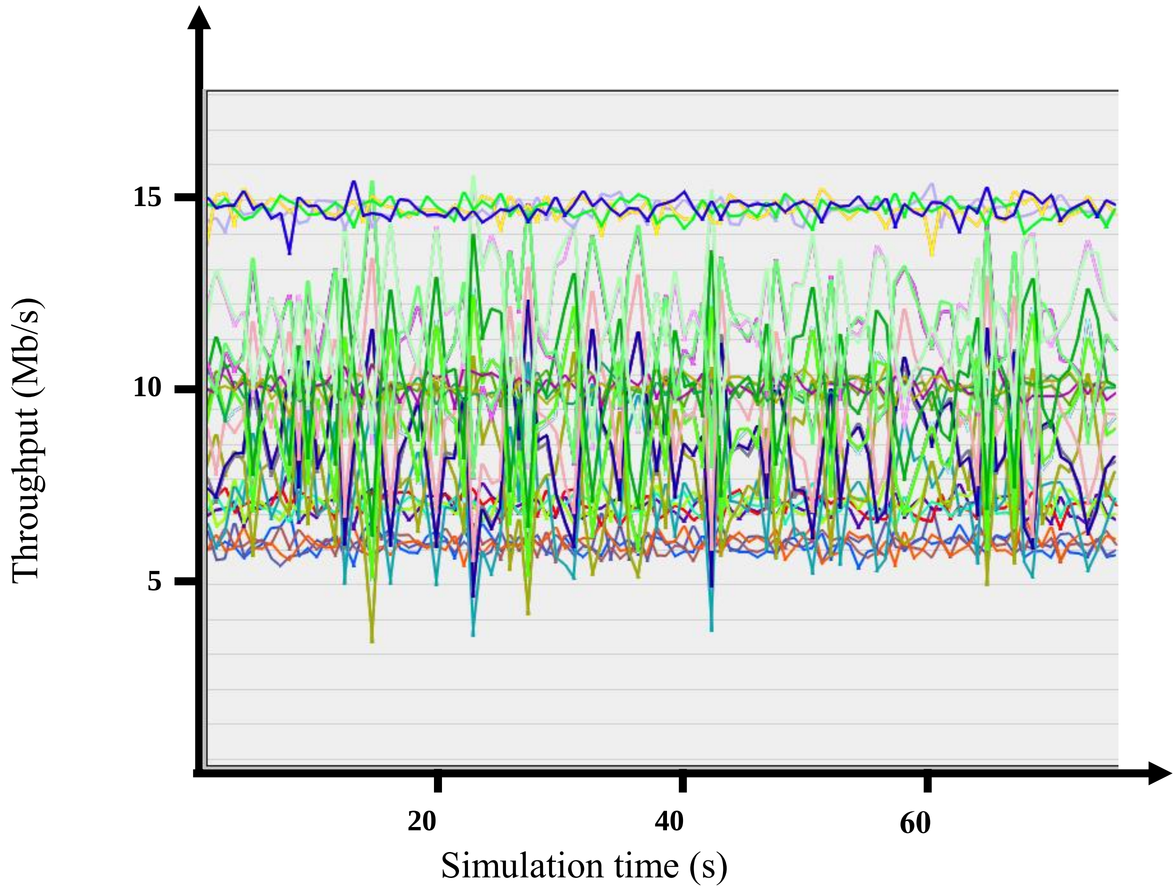


**Figure 21:** Throughput per device vs. simulation time for 70 dB isolation between the apartments. The different traces are the observed throughputs for every single device.

## 4.4 Simulation results for manual channel assignment

Figure 22 shows the results for a channel assignment one finds in typical apartment blocks: people who know what they are doing configure their AP such that they operate on a “free channel”. Also some basic channel assignment algorithms produce similar configurations. All results are average throughputs per apartment, averaged over 3 simulation runs of one minute each, and using seeds 11, 22 and 33. The average throughput over all apartments is 2.18 Mb/s. This is only marginally better than what we found if all channels are assigned to 1 (first bar in Figure 19). From this we conclude that people trying to “find a free channel” manually does not solve anything, because adjacent channel interference has quite a devastating effect on the overall performance.

Strangely some apartments seem to get a very good performance despite the large amount of adjacent channel interference. This result is reproducible, except for which apartments get the better performance. It seems that adjacent channel interference is often not equally harmful to the involved apartments, but that it is unpredictable which apartment “wins” and the result may change quickly over time. Further study of this effect is planned for the future.

| | | | | |
|---|---|---|---|---|
| 1 | | 6 | | 3 |
| | 11 | | 4 | |
| 6 | | 11 | | 1 |
| | 4 | | 1 | |
| 1 | | 9 | | 11 |
| | 11 | | 1 | |
| 6 | | 11 | | 11 |
| | 6 | | 8 | |

| | | | | |
|---|---|---|---|---|
| 0.22 | | 0.24 | | 13.36 |
| | 0.18 | | 0.00 | |
| 0.36 | | 0.22 | | 0.19 |
| | 6.62 | | 0.30 | |
| 0.21 | | 19.99 | | 0.26 |
| | 0.22 | | 0.31 | |
| 0.26 | | 0.19 | | 0.23 |
| | 0.26 | | 0.00 | |

**Figure 22:** A typical channel assignment (left-hand side diagram) and average throughput per apartment (right-hand side diagram) in apartment blocks

Also some of the other apartments show interesting results. For instance, the most left-hand apartment on the top floor (row 1, column 1 in Figure 22) does not suffer adjacent channel interference from any of his direct neighbours or the apartment straight below, which all use either channel 6 or 11. Nevertheless, its Wi-Fi performs badly because the apartment diagonally below uses channel 4, and that already seems to cause too much adjacent channel interference. Also, the fourth apartment on the top floor (row 2, column 4) has two apartments directly opposite, one straight below, and one diagonally below causing adjacent channel interference, apparently leading to no measurable throughput at all. A similar story holds for the fourth apartment on the ground floor (row 8, column 4).

We now imagine a case where the residents are well aware of the problem and try to "manually" agree on a channel assignment, avoiding adjacent channel interference as much as possible. The resulting channel assignment could very well look like the one shown on the left hand side of Figure 23: no closest neighbours (i.e. the apartments directly above and below, the apartments to the left and right, and the apartments directly opposite) share a channel. The right hand side of Figure 23 shows the resulting performance of Wi-Fi. The average throughput over all apartments is now 5.42 Mb/s, which is significantly more than the previous cases. However, for the middle two apartments there is hardly any improvement. Worse even, for some apartments the results are worse compared to the situation shown in Figure 22. These residents may therefore choose not to collaborate in the joint channel assignment negotiation. This situation is further elaborated in D2.6 [16].

| | | | | |
|---|---|---|---|---|
| 1 | | 6 | | 11 |
| | 11 | | 1 | |
| 6 | | 11 | | 1 |
| | 1 | | 6 | |
| 11 | | 1 | | 6 |
| | 6 | | 11 | |
| 1 | | 6 | | 11 |
| | 11 | | 1 | |

| | | | | |
|---|---|---|---|---|
| 7.11 | | 2.56 | | 8.58 |
| | 8.01 | | 4.27 | |
| 7.40 | | 1.00 | | 7.63 |
| | 3.73 | | 2.30 | |
| 7.55 | | 1.21 | | 8.74 |
| | 2.54 | | 3.57 | |
| 8.67 | | 3.82 | | 7.72 |
| | 4.16 | | 7.91 | |

**Figure 23:** Average throughput per apartment for a typical channel assignment "manually" agreed upon between residents with avoidance of adjacent channel interference.

Figure 23 also confirms our hypothesis regarding the first apartment on the top floor as discussed with Figure 22: the only difference between Figure 23 and Figure 22 in terms of channel assignment of the direct neighbours is that the apartment in row 4, column 2 now switches from channel 4 to channel 1, and the adjacent channel interference has been eliminated.

## 4.5 Simulation results for the Wi-5 channel assignment algorithm

In Wi-5, we assume that more spectrum can be saved if the channels are assigned automatically by a centralised controller managing all APs in the apartment block. The architecture for such a system is described in Deliverable 2.5i [21]. The controller configures the APs using a set of algorithms that optimise the system-wide performance by means of channel assignment, transmit power control, horizontal and vertical handover, and smart packet grouping, as illustrated in Figure 24.

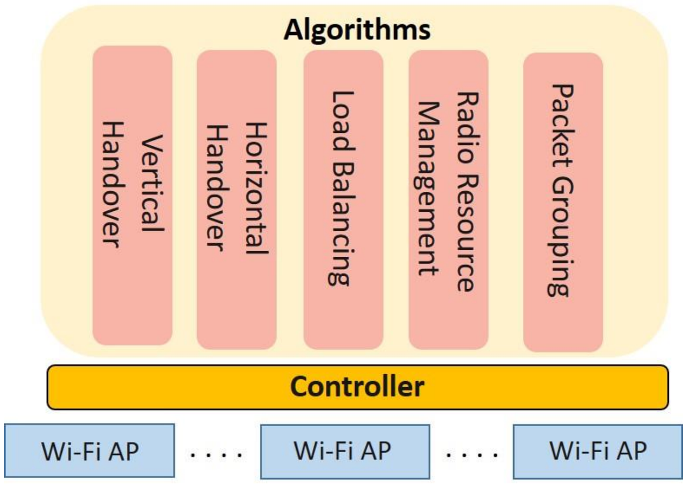


**Figure 24:** Wi-5 general architecture

The channel assignment algorithm is based on an objective function that represents the inter-relation between APs due to their arrangement in terms of channel configuration and mutual interference impacts, and is able to reduce the magnitude of this interference in the system as a whole. In detail, this strategy allows the Wi-5 controller to find an optimised channel distribution, in terms of interference for the different APs, in a network based on (i) the Wi-Fi system properties (e.g. IEEE 802.11's standard channel characteristics); (ii) the logical network topology (the AP distribution throughout the network); and (iii) the desired resource management criteria (the assigned channels, interference related QoS, or handover requirements). A detailed description of the channel assignment algorithm is included in D4.2 [2].

Applying this algorithm to our use case yields the channel assignment as shown in the left-hand side of Figure 25. The resulting Wi-Fi performance is shown in the right-hand side. Like is the case in Figure 23, for some apartments the results are worse compared to the situation shown in Figure 22. These residents may therefore choose not to collaborate in the joint channel assignment negotiation. However, compared to the results obtained for the case where the residents are well aware of the problem, but try to "manually" agree on a channel assignment (see Figure 23), the results shown in Figure 25 seem much more "fair". It will therefore be more likely that everybody will participate in the collaboration anyway, even though a few apartments will experience a somewhat less (though still reasonable) performance compared to the unmanaged scenario of Figure 22. The average throughput over all apartments is now 4.60 Mb/s, which is only marginally less than found for the situation in Figure 23.

For now, we assumed that "fair" means an equal performance per apartment. In reality, of course, what is "fair" is whatever the residents agree upon in their negotiation with each other [16]. The algorithm as described above, however, is flexible enough to have any agreed upon quality distribution over the apartments as an input, and calculate the optimal channel assignment accordingly.

| | | | | |
|---|---|---|---|---|
| 1 | | 6 | | 1 |
| | 11 | | 1 | |
| 6 | | 11 | | 1 |
| | 6 | | 6 | |
| 1 | | 11 | | 11 |
| | 11 | | 1 | |
| 6 | | 11 | | 11 |
| | 6 | | 1 | |

| | | | | |
|---|---|---|---|---|
| 3.55 | | 4.39 | | 4.53 |
| | 3.88 | | 5.06 | |
| 5.29 | | 4.60 | | 4.17 |
| | 5.18 | | 5.02 | |
| 3.78 | | 4.33 | | 5.02 |
| | 4.17 | | 5.42 | |
| 5.06 | | 4.27 | | 4.98 |
| | 4.11 | | 5.16 | |

**Figure 25:** Average throughput per apartment for the channel assignment as found by the Wi-5 algorithm.

For now, we only looked at channel selection in the 2.4 GHz band. We show that AP operators agreeing on an intuitive channel distribution avoiding adjacent channel interference provide significant improvement. However, we also show that applying a new, more intelligent algorithm provides significant additional improvements:

- The outcome of the algorithm provides the fairest outcome, whereas “fair” can be defined by any agreement among the AP operators, which increases the chance that all AP operators will actually participate in the collaboration.
- The algorithm can be easily extended with other mechanisms which optimizes the spectrum usage even further, such as transmit power control, hand-overs, and smart packet grouping.

In theory, the algorithm can be applied “offline”, i.e. people just manually configure their APs according to the channel distribution obtained from the algorithm after it is fed with the agreed upon input parameters. However:

- the optimal distribution will change over time, which would require repetitive manual configuration,
- many people do not know how to configure their APs,
- even better results can most likely be obtained by also taking transmit power, hand-over, and packet grouping functionalities into account, which are even harder to configure manually.

We therefore recommend that the optimisation algorithm is run in real-time on an intelligent central controller which automatically configures the APs, like the one being developed in the Wi-5 project.

# 5 Conclusions

This deliverable expands on the use cases most relevant to Wi-5 as presented in D2.3 [1], and answers two research questions:

1) Would a solution such as Wi-5 fit into the roadmaps that operators and vendors are currently using for their Wi-Fi deployment?
2) Can we quantify the effect that the Wi-5 solutions have on the actual performance of Wi-Fi systems as used in the current use cases?

Regarding the first question, we conducted a survey among six European operators. From the survey, we can conclude that by and large the operators intend to keep following the Wi-Fi Alliance product roadmap with regard to their Wi-Fi deployment plans, given the needs of their customers. It can therefore be safely stated that the operators' Wi-Fi roadmap is just an extension of the IEEE 802.11 technology roadmap as presented in section 2.

As of today, the most popular version of the standard is IEEE 802.11n being present in both the 2.4 and 5 GHz bands. An interesting observation can be made about version IEEE 802.11b and 802.11a. Even though they are present in the networks of 10-15% of the operators, which is quite a lot given the fact that these technologies are nearly twenty years old, they only account for under 1% of their deployments. This is true across all of the considered subsets of operators. This means that for the 2.4 GHz band the only relevant versions are 802.11g and 802.11n, while for the 5 GHz band, versions 802.11n and 802.11ac are the relevant ones. However, it is known that even this 1% of 802.11a and .11b (mostly .11b) causes quite a lot of interference and performance problems, especially in mixed version Wi-Fi networks, which explains why operators are seriously concerned with upgrading their legacy deployments as soon as possible. The preferred choice of version to update is IEEE 802.11n, but some operators are already considering a change to IEEE 802.11ac Wave1 and Wave2 deployments.

The Wi-Fi use cases that seem to be most relevant for most of the operators are:

- Airport/train station in the case of Operators under 1M (million) customers,
- Dense apartment building for operators above 1M customers
- Large home/SOHO for Operators above 10M customers.

Out of these the dense apartment building stands out as being very important for all considered subsets of operators. It is therefore that we focused on this use case only to answer our research question 2).

The questionnaire also revealed that out of all the customers that report a technical problem to their operator within a year, on average one in four reports a Wi-Fi related problem. This is quite significant and would translate to hundreds of thousands of help desk calls per operator per year. From the results of the questionnaire regarding the business aspects of Wi-Fi, we can therefore conclude that the costs for solving these Wi-Fi problems are currently in the millions of euros per operator per year.

We therefore conclude that the answer to the first research question is "yes":

- Deliverables D2.1 [15] and D2.6 [16] show that viable business models exist for successful deployment of Wi-5.
- Even though most of the operators consider the 5 GHz band as a solution to the current congestion in the 2.4 GHz band, they also welcome the idea of managing the existing 2.4 GHz

Wi-Fi environment better than what is done today. The latter is what Wi-5 is promising to deliver.

- It is important that Wi-5-like solutions become part of the IEEE 802.11 and Wi-Fi Alliance roadmap. This is not an unreasonable assumption, as management solutions (e.g. 802.11k) are already part of their roadmap, and also SDN is already well accepted by the industry, but requires effort from the industry partners affiliated to the project.

Regarding the second research question, we performed a first quantitative modelling of the dense apartment deployment use case regarding various spectral efficiency performance indicators, such as throughput per apartment, and average throughput for the complete apartment block. This is the first time that such a Wi-Fi performance evaluation is done for a 3D environment.

The simulations clearly indicate that over-congestion is indeed a problem in current dense apartment block Wi-Fi deployments. For now, we only looked at how smart channel selection could relieve the issue in the 2.4 GHz band. We then showed that current adaptive but non-collaborative channel selection procedures have only little effect: they typically lead to very destructive adjacent channel interference. Some form of collaboration between AP operators is therefore clearly needed to solve the problem.

We then showed that AP operators agreeing on an intuitive channel distribution avoiding adjacent channel interference already provides significant performance improvement. However, it may also lead to a grossly unfair distribution of resources over the individual apartments. This may lead to some residents defecting from the collaboration, and consequently trying out configurations which may give them a slightly better performance, but which are devastating for their neighbours.

This issue is then ultimately solved by applying the Wi-5 channel selection algorithm. This algorithm aims to find an optimal channel assignment which minimizes the interference impact, and we show in our simulations that this indeed leads to a fair assignment (i.e. the throughputs of all apartments are expected to be similar). As this does not guarantee that every apartment will obtain a better performance compared to the fully unmanaged case, neither does it fully guarantee that nobody will defect from the collaboration. However, as now everybody will agree that the resulting performance distribution is fair (where “fair” may also be pre-defined by any other agreement of performance distribution among the AP operators, and fed as such into the algorithm), it will be significantly more likely that everybody will participate in the collaboration anyway.

In theory, the algorithm can be applied “offline”, i.e. people just manually configure their APs according to the obtained channel distribution. However:

- the optimal distribution will change over time, which would require repetitive manual configuration,
- many people do not know how to configure their APs,
- even better results can most likely be obtained by also taking transmit power, hand-over, and packet grouping functionalities into account, which are even harder to configure manually.

We therefore recommend that the optimisation algorithm is run in real-time on an intelligent central controller which automatically configures the APs.

Future work includes:

- Performing further simulation for other Wi-Fi versions, including the 5 GHz band, and for more realistic traffic patterns,

- Simulating the effect of an improved algorithm, including transmit power control, horizontal handover, vertical handover, and smart packet grouping,
- Performing real-life measurements in dense apartment blocks like the one simulated,
- Investigating the effect of having non-collaborating AP operators in the apartment block.

## References


[1] Berberana, I. (2015), Wi-5 use cases and requirements, Deliverable 2.3 of the H2020 Wi-5 project;

[2] Raschella, A., et al, (2017), Specification of Cooperative Access Points Functionalities version 2, Deliverable 4.2 of the H2020 Wi-5 project;

[3] J. Kim, I. Lee, (2015), 802.11 WLAN: History and New Enabling MIMO Techniques for Next Generation Standards, IEEE Communications Magazine, pp. 134-140;

[4] M. Mishra and A. Sahoo, (2006), A Contention Window Based Differentiation Mechanism for providing QoS in Wireless LANs, Information Technology, 2006. ICIT '06. 9th International Conference on, Bhubaneswar, 2006, pp. 72-76;

[5] T. Nadeem, (2010), Analysis and Enhancements for IEEE 802.11 Networks Using Directional Antenna With Opportunistic Mechanisms, IEEE TRANSACTION ON VEHICULAR TECHNOLOGY, VOL. 59, NO. 6, JULY 2010, pp. 3012-3024;

[6] M. Naghibi, M. Ghaderi, (2014), Characterizing the Peformance of Beamforming WiFi Access Points, 39th Annual IEEE Conference on Local Computer Networks LCN 2014, Edmonton, Canada, pp. 434-437;

[7] S. Wendt, A. Chicot and M. Skrok, (2014), On beamforming performance in Wi-Fi outdoor networks, 2014 11th International Symposium on Wireless Communications Systems (ISWCS), Barcelona, 2014, pp. 338-342;

[8] S. L. Ariyavisitakul, J. Zheng, E. Ojard and J. Kim, (2008), Subspace Beamforming for Near-Capacity MIMO Performance, in IEEE Transactions on Signal Processing, vol. 56, no. 11, pp. 5729-5733, Nov. 2008;

[9] L. Deek, E. Garcia-Villegas, E. Belding, S. J. Lee and K. Almeroth, (2013), Joint rate and channel width adaptation for 802.11 MIMO wireless networks, 2013 IEEE International Conference on Sensing, Communications and Networking (SECON), New Orleans, LA, 2013, pp. 167-175;

[10] G. Redieteab, L. Cariou, P. Christin and J. F. Hélard, (2012), SU/MU-MIMO in IEEE 802.11ac: PHY+MAC performance comparison for single antenna stations, Wireless Telecommunications Symposium (WTS), 2012, London, 2012, pp. 1-5;

[11] Daji Qiao and Sunghyun Choi, (2006), New 802.11h mechanisms can reduce power consumption, in IT Professional, vol. 8, no. 2, pp. 43-48, March-April 2006;

[12] I. Wang-Hei Ho and S. Chang Liew, (2007), Impact of Power Control on Performance of IEEE 802.11 Wireless Networks, in IEEE Transactions on Mobile Computing, vol. 6, no. 11, pp. 1245-1258, Nov. 2007;

[13] W. H. Ho and S. C. Liew, (2006), Distributed Adaptive Power Control in IEEE 802.11 Wireless Networks, 2006 IEEE International Conference on Mobile Ad Hoc and Sensor Systems, Vancouver, BC, 2006, pp. 170-179;

[14] W. Sun, M. Choi, S. Choi, (2013), IEEE 802.11ah: A Long Range 802.11 WLAN at Sub 1 GHz, Journal of ICT Standardization, Vol. 1, pp. 83–108;

[15] Dittrich, K., den Hartog, F. (2015). Viability of business models for multi-operator Wi-Fi coordination platforms, Deliverable 2.1 of the H2020 Wi-5 project;

[16] F. den Hartog, et al (2016). Regulatory and game-theoretical considerations regarding the Wi-5 business model, Deliverable 2.6 of the H2020 Wi-5 project;

[17] J. P. de Vries et al, “The Emperor has no Problem: Is Wi-Fi spectrum really congested?,” in the 41st Research Conference on Communication, Information and Internet Policy (TPRC), 2013;

[18] A. Ozyagci, K. W. Sung, and J. Zander, “Effect of propagation environment on area throughput of dense WLAN deployments,” in 2013 IEEE Globecom Workshops (GC Wkshps), 2013, pp. 333–338;

[19] R. Rudd, K. Craig, M. Ganley, and R. Hartless, Building Materials and Propagation, Final Report, Ofcom, 2604/BMEM/R/3/2.0 (2014).

[20] 3Com Wireless Antennas Guide (2005). lojati.com.br/Customer/Datasheets/3CWE598.pdf

[21] Bouhafs, F., *et al* (to be published), interim version of the Wi-5 final architecture, Deliverable 2.5i of the H2020 Wi-5 project.

[22] K. Zhou, X. Jia, L. Xie, Y. Chang, and X. Tang, “Channel Assignment for WLAN by Considering Overlapping Channels in SINR Interference Model”, International Conference on Computing, Networking and Communications (ICNC), Maui, Hawaii, USA 30 Jan.- 2 Feb. 2012.

# Annex A: Operator Board Wi-Fi survey questions

## Operator Board Wi-Fi Survey

About this survey

This questionnaire is meant to identify the most common type of Wi-Fi problems encountered in the deployments of operators. This survey was sent out in the context of the Wi-5 project to members of the Operator Board. As part of developing a Wi-Fi solutions roadmap it is important to understand the exact circumstances in which Wi-Fi problems occurs. Details about the services provided, Wi-Fi versions and deployment environments, will ensure that the information is aligned, not only with the technical specificity of the problems, but also with the business models of operators.

* Required

### Context of operator and the Wi-Fi deployments

This section is meant to understand the services that the operator is providing and the context of their Wi-Fi deployments.

### 1. What is the total number of clients that use your broadband services?

1. *

*Mark only one oval.*

- less than 1.000
- between 1.000 and 10.000
- between 10.000 and 100.000
- between 100.000 and 1.000.000
- between 1.000.000 and 10.000.000
- more than 10.000.000

### 2. What is the number of clients which make use of Wi-Fi?

2. *

*Mark only one oval.*

- less than 1.000
- between 1.000 and 10.000
- between 10.000 and 100.000
- between 100.000 and 1.000.000
- between 1.000.000 and 10.000.000
- more than 10.000.000

### 3. What are the services you support via broadband connections?

3. *

Choose all options which match your situation, from the following selection.
*Check all that apply.*

- [ ] N/A
- [ ] Residential Internet access
- [ ] Enterprise Internet access
- [ ] IP-TV - managed by the operator (e.g. local television, local radio, video on demand, etc.)
- [ ] Internet-TV - unmanaged by the operator (e.g. Netflix, Youtube, etc.)
- [ ] VoIP - (e.g. home fixed digital telephony, etc.)
- [ ] Wireless access infrastructure for enterprise
- [ ] Wireless access in public spaces - authentication based access
- [ ] Wireless access in public spaces - agreement based access (no authentication required)
- [ ] Third party access on customers' broadband access (e.g. FON)
- [ ] Other: ____________________

## 4. Which of these services make use of Wi-Fi?

4. *

Choose the top five most relevant options, which best describe your situation, from the following selection.
*Check all that apply.*

- [ ] None
- [ ] Residential Internet access
- [ ] Enterprise Internet access
- [ ] IP-TV - managed by the operator (e.g. local television, local radio, video on demand, etc.)
- [ ] Internet-TV - unmanaged by the operator (e.g. Netflix, etc.)
- [ ] VoIP - (e.g. home fixed digital telephony, etc.)
- [ ] Wireless access infrastructure for enterprise
- [ ] Wireless access in public spaces - authentication based access
- [ ] Wireless access in public space - agreement based access (no authentication required)
- [ ] Third party access on customers' broadband access (e.g. FON)
- [ ] Other: ____________________

## 5. What Wi-Fi versions are deployed for your customers?

5. *

Choose the top three from the following selection.
*Check all that apply.*

- [ ] IEEE 802.11 a / IEEE 802.11 b
- [ ] IEEE 802.11 g
- [ ] IEEE 802.11 n - 2.4GHz
- [ ] IEEE 802.11 n - 5GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ____________

## 6. What is the distribution among deployed versions?

6. **IEEE 802.11 a / IEEE 802.11 b**

*Mark only one oval.*

- ( ) 0-10%
- ( ) 11-20%
- ( ) 21-30%
- ( ) 31-40%
- ( ) 41-50%
- ( ) 51-60%
- ( ) 61-70%
- ( ) 71-80%
- ( ) 81-90%
- ( ) 91-100%

7. **IEEE 802.11 g**

*Mark only one oval.*

- ( ) 0-10%
- ( ) 11-20%
- ( ) 21-30%
- ( ) 31-40%
- ( ) 41-50%
- ( ) 51-60%
- ( ) 61-70%
- ( ) 71-80%
- ( ) 81-90%
- ( ) 91-100%

8. **IEEE 802.11 n - 2.4GHz**
*Mark only one oval.*

- ◯ 0-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60%
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

9. **IEEE 802.11 n - 5GHz**
*Mark only one oval.*

- ◯ 0-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60%
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

10. **IEEE 802.11 ac**
*Mark only one oval.*

- ◯ 0-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60%
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

11. **Other version**

______________________________

12. Please mention the other version before selecting a value (if applicable).
*Mark only one oval.*

- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 7. Which of the following use cases are suitable to describe the situation of your Wi-Fi services and what is the distribution of each?

13. **Airport / train station** *
The Airport / Train Station use case addresses the typical network deployments found in public places, where a number of Wi-Fi APs are used to provide coverage to users in the area. This use case falls in the category high density of APs and high density of STAs per AP.
*Mark only one oval.*

- N/A
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

14. **Apartment building** *

The apartment building use case corresponds to a Wi-Fi scenario where the tenants in each apartment arrange their broadband connection independently. The broadband connection in each apartment can be provided by different service providers, such as cable providers, telecom operators and mobile operators. The Wi-Fi APs in each apartment, either provided by operators or bought from a shop, are installed and configured in an unmanaged manner. As a result, Wi-Fi APs may severely interfere with each other. This severe interference results in inefficient usage of the unlicensed and unmanaged wireless spectrum.

*Mark only one oval.*

- N/A
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

15. **Pico-cell street deployment** *

Operators are building 3G/4G networks with large overlay cells for coverage and micro cells for local capacity that are seamlessly integrated into a single network. The addition and integration of Wi-Fi small or pico-cells to locally provide an even higher capacity in public areas like shopping streets and squares with terraces. As an off-load network, the pico-cell street network will specifically serve nomadic users, pedestrians and other users with a low speed; all high speed users will remain on the overlay 3G/4G network. As such, the service demand of this use case will encompass a wide range of services, including common Internet access for browsing, telephony (VoIP), streaming audio and video and online gaming

*Mark only one oval.*

- N/A
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

16. **Large home / SOHO** *

The Large home or Small Office / Home Office (SOHO) use case is a common Wi-Fi scenario which has evolved beyond a simple deployment around a single, central AP. It may have specific wireless resource restrictions, or the coverage needs to extend over a wide area, so the user may need multiple APs in the same property. Users will expect the wireless network to support a wide range of applications and services simultaneously which might include a mix of traditional Internet applications such as web/email, high bandwidth services like video streaming or large data transfers, or demanding applications such as VoIP/Video Conferencing or online gaming. Users may also have a degree of local mobility, that is they may move between rooms in the property, and expect to remain constantly connected.

*Mark only one oval.*

- N/A
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

17. **Community Wi-Fi** *

Community Wi-Fi networks allow operators to offer Wi-Fi network access to their on-the-go subscribers by using existing residential and Small Medium Businesses (SMB) Wi-Fi infrastructure – if the owners of the infrastructure agree with the provision of the service. Operators can also use this coverage to offer services to retail and roaming partner operators' subscribers. The service allows the user access to the network resources of other Community Wi-Fi subscribers when out of his home. The service level that the user can get in the visited networks is established based on the subscription contract to the service, and it should never result in a loss of QoE for the hosting users. In exchange, the user allows other Community Wi-Fi users to connect to their home network in return.

*Mark only one oval.*

- N/A
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

18. **Other use case?** *

Is there another use case relevant for your situation?
*Mark only one oval.*

- ◯ No other use case. *Skip to question 22.*
- ◯ Other use case, namely... *Skip to question 19.*

## 7. Other use case

19. **Name:** *

Please enter the name of the use case:

..............................................................................

20. **Description:** *

Please describe briefly this use case:

..............................................................................
..............................................................................
..............................................................................
..............................................................................
..............................................................................

21. *

With a distribution of:
*Mark only one oval.*

- ◯ 1-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60%
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

## 8. How many technically related customer complaints do you receive per year?

22. *

*Mark only one oval.*

- less than 1.000
- between 1.000 and 10.000
- between 10.000 and 100.000
- between 100.000 and 1.000.000
- more than 1.000.000

## 9. How many of the customer complaints you receive are for Wi-Fi related problems?

23. *

*Mark only one oval.*

- None *Skip to "Solutions for Wi-Fi."*
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 10. How many of the Wi-Fi related complaints fall into each of the following types of problems?

24. **No connectivity** *

No uptime since problem encountered.

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60
- 61-70%
- 71-80%
- 81-90%
- 91-100%

25. **Poor connectivity** *

Some uptime since problem encountered.
*Mark only one oval.*

- ◯ 0-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

26. **Poor service performance** *

100% uptime; throughput problem.
*Mark only one oval.*

- ◯ 0-10%
- ◯ 11-20%
- ◯ 21-30%
- ◯ 31-40%
- ◯ 41-50%
- ◯ 51-60
- ◯ 61-70%
- ◯ 71-80%
- ◯ 81-90%
- ◯ 91-100%

27. **Other**

______________________________

28. Please provide a name and write a brief description before selecting a value (if applicable).
*Mark only one oval.*

- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## Solutions for Wi-Fi

This section focuses on the potential solutions for Wi-Fi issues.

## 11. In which of the following price categories does the average cost for handling Wi-Fi related problems fall into?

29. *
*Mark only one oval.*

- less than 5 €
- between 6 € and 10 €
- between 11 € and 15 €
- between 16 € and 20 €
- between 21 € and 25 €
- 26 € or more
- Unknown

## 12. In which of the following price categories does the average cost for a "truck-roll" (on site assistance) fall into?

30. *
*Mark only one oval.*

- less than 50 €
- between 51 € and 60 €
- between 61 € and 70 €
- between 71 € and 80 €
- 81 € or more
- Unknown

## 13. How often do Wi-Fi related complaints escalate to

## "truck-rolls"?

31. *

*Mark only one oval.*

- Never
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 14. How often is the solution adopted for Wi-Fi problems implemented remotely?

32. *

*Mark only one oval.*

- Never
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 15. How often is a problem with Wi-Fi related to some other misconfiguration (DHCP, firewall, etc.) ?

33. *

*Mark only one oval.*

- Never
- 1-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 16. How many of the Wi-Fi issues are related to each of the following version?

34. **IEEE 802.11 a / IEEE 802.11 b** *

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

35. **IEEE 802.11 g** *

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

36. **IEEE 802.11 n - 2.4Ghz** *

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

37. **IEEE 802.11 n - 5Ghz** *

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

38. **IEEE 802.11 ac** *

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

39. **Other**

_______________________________________________

40. Please provide a version before choosing a value (if applicable).

*Mark only one oval.*

- 0-10%
- 11-20%
- 21-30%
- 31-40%
- 41-50%
- 51-60%
- 61-70%
- 71-80%
- 81-90%
- 91-100%

## 17. Do you plan to changing the Wi-Fi version for any of your services?

41. *

*Mark only one oval.*

- Yes *Skip to question 42.*
- No *Skip to question 55.*

## 17. From which of the following versions to which versions and why?

42. **From IEEE 802.11 a / IEEE 802.11 b to ...**
*Check all that apply.*

- [ ] IEEE 802.11 g
- [ ] IEEE 802.11 n - 2.4Ghz
- [ ] IEEE 802.11 n - 5GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ________

43. ... because:

________

44. **From IEEE 802.11 g to ...**
*Check all that apply.*

- [ ] IEEE 802.11 n - 2.4GHz
- [ ] IEEE 802.11 n - 5GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ________

45. ... because:

________

46. **From IEEE 802.11 n - 2.4GHz to ...**
*Check all that apply.*

- [ ] IEEE 802.11 n - 5GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ________

47. ... because:

________

48. **From IEEE 802.11 n - 5GHz to ...**
*Check all that apply.*

- [ ] IEEE 802.11 n - 2.4GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ________

49. ... because:

________

50. **From IEEE 802.11 ac to ...**
*Check all that apply.*

- [ ] Other: ____________

51. ... because:

____________

52. **From other, namely...**
Please fill in the name of the other version.

____________

53. **... to ...**
Please check the version(s) that will replace the other version.
*Check all that apply.*

- [ ] IEEE 802.11 g
- [ ] IEEE 802.11 n - 2.4GHz
- [ ] IEEE 802.11 n - 5GHz
- [ ] IEEE 802.11 ac
- [ ] Other: ____________

54. ... because:

____________

## 18. Do you see the need for a standardised method for detecting and resolving Wi-Fi problems?

55. *

____________
____________
____________
____________
____________

## End of survey

The deadline of the survey has been extended.

The results of the survey will be shared back as soon as enough respondents have completed it, in order to have a sufficient pool of answers to further obtain a meaningful set of results from.

Powered by Google Forms