Universidad de Alcalá
Escuela Politécnica Superior

Grado en Ingeniería en Tecnologías de la Telecomunicación

Trabajo Fin de Grado

Implementation of Improvements of the Wi-Fi Network of the RTBF and Implementation of a Wi-Fi Network for an "Intelligent" Building

ESCUELA POLITECNICA SUPERIOR

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“We are all now connected by the Internet,
like neurons in a giant brain.”

- *Stephen Hawking*

Thank You Note

This note of thanks is directed to all those who have helped me, from near and far, to undertake and complete this degree, which concludes with this graduation work.

To my family, for all the support they have given me throughout my studies and for the sacrifices and hardships they have face so that I can achieve my goals. They have been pillars in my life choices and in my personality and have helped, and still are, to make the person I am today. They have been an example in terms of moral support, always ready to face a challenge at my side. For all these reasons and more, they have allowed me to achieve an important goal for me, to finish my career.

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Finally, to all the professors of the University for your dedication, for the time you offer to your students and for forming us into Engineers. After a long stay at the University, I can say that I have learned a lot of new contents and concepts and new ways of thinking.

With this work I finish a stage of my life, perhaps not the easiest but certainly one of the most interesting and constructing so far. I learned a lot academically, humanly and also on my own. Each of the people mentioned taught me something during this learning and that is why I thank them.

To you all, thank you.

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Resumen

Este Trabajo de Fin de Grado se ha realizado dentro de la Radio Televisión Belga Francófona (RTBF) en Bruselas. El objetivo de este proyecto es el diseño de una red Wi-Fi completamente confiable y de alto rendimiento para una de sus localizaciones.

Para empezar, se completaron un estudio teórico y mediciones reales. La comparación entre el estudio teórico y práctico no estaba concluyente por lo que las predicciones teóricas se han modificado para corresponder a la realidad.

Finalmente, la RTBF está construyendo un nuevo edificio en 2022 para el cual un estudio predictivo teórico se ha hecho para proporcionar una cantidad de puntos de accesos necesarios para una cobertura completa.

Palabras Claves

802.11 Estandard, Tecnologías de Puntos de Accesos, Implementación de Red, Prediciones Futuras.

Resume

This End-of-Grade work have been done inside the Francophone Belgian Radio-Television (RTBF) in Brussels. The goal of this Project is to design a fully reliable and performant Wi-Fi network for one of their localization.

To begin with, a theorical study and real-life measurements were completed. The comparasion between the theorical and practical study was not concluding so the theorical predictions have been changed to correspond to reality.

Finally, the RTBF is constructing a new building in 2022 for which a theorical predictive study have been done to provide the number of needed access points for a complete coverage.

Key Words

802.11 Standard, Access Point Technologies, Network Implementation, Future Predictions.

Extended Resume

The 802.11 standard appeared around 1997. Since then, the standards and infrastructures involved in the Wi-Fi implementation have changed and evolved with the changing society. In 2007, in an office environment, one person out of four owned a wireless device. Ten years later, in 2017, every person in that office owns around three wireless devices. This End-of-Grade project propose to go through this evolution, from the beginning of 802.11 standards history through to the implementation of an upgraded Wi-Fi infrastructure.

This work, studying the implementation of a Wi-Fi network was realized on one of the localizations of the RTBF (Francophone Belgian Radio-Television), an autonomous public company with a cultural character that is active in television, radio, Internet and social networks. The main goal of this project is to create an improved implementation of the Wi-Fi network currently used in the Reyers site (1000 workers) of the RTBF regarding the existing issues. The problematics of this building is the lack of coverage, being a construction of the 1950’s, the construction is thick and involves heavy attenuations of the electromagnetic signals.

The best way to improve an existing Wi-Fi network is to make a proper site-survey of the building. At a site-survey, it is easier to understand what are the existing needs of the building (where people work, where there is a lot of workers at the same time, etc.) and what are the most important problems for wireless transmissions (characteristics of transmissions, attenuations and interferences).

The characteristics of transmissions, if well chosen, can reduce interferences and power consumption. For example, by choosing the right band to transmit, the signal can avoid being interfered by Bluetooth, microwave oven, wireless microphones, etc. Moreover, the type and characteristics of the 802.11 modules at both ends of the communication (the receiver and the transmitter) and the choice of antenna are vital to make a precise calculation of the coverage range. The Wi-Fi standard can be affected by many attenuations due to the indoor environment. The electromagnetic signals properties are such that they suffer from reflection, diffraction and scattering. So, depending on the number of obstacles and their materials characteristics, an electromagnetic signal can be more attenuated then others.

After a full site-survey of the localization, the main problematic encountered were the building itself because of the construction’s properties, the existing access points placement which where partly wrongly installed and also the high number of Rogues Access Points which interferes with the actual secured Wi-Fi network by working on the same channels.

In order to make the more precise calculations of coverage, it is important to be fully aware of the wireless transmission characteristics and the constructions material. For this reason, after a study was realized on the characteristics needed for the coverage calculations, many measures were taken to be able to compute the exact attenuations due to the different construction materials.

The calculations of the total path loss are based on the IUT-R P.1238 recommendation, which provide predictive methods for the planning of indoor wireless communication systems between 300 MHz and 100 GHz. The combination of the path loss equation of the general model of this recommendation with the material loss provide the equation of the total path loss of an electromagnetic signal in the office environment for the Reyers localization of the RTBF.

The RTBF already owns four series of Cisco Access Points. The specific characteristics of those access points, such as the antenna gain, and transmitting power, among with the features of two chosen end-point Wi-Fi modules allow to obtain the total path loss of the different access points. With the purpose of calculating the radii of coverage of the available access points, the Friis equation permit to calculate the distance of coverage depending on the transmit power, the total path losses and the receiver sensitivity.

So as to guarantee a reliable communication at the calculated coverage distance, a probability to ensure that the desired signal strength is received is fixed at 75%. This probability, among with the previously calculated distance of coverage and other parameters, permits to calculate the real radii of coverage. Finally, from that real radii of coverage and the distance between two access points, it is possible to calculate the coverage factor of this network which is 39.29%.

After the theorical calculation was completed, a comparation of these results with real measurement were executed. The conclusion was negative, with a difference of various meters, the theorical calculations being worst than the reality. To understand such a difference in the results, the theorical distance calculations had to be reconsidered, using lower probabilities to obtain the desired signal power, in order to coincide the distance of coverage in theory and in reality. By using a probability of 50%, the radii of coverage theorically calculated matched perfectly, with a maximum deviation of around 10 cm. Since there are no better experiment then reality measurements, it was chosen that the radii calculated with a signal strength probability of 50% would be the one used in the design of the Wi-Fi infrastructure.

To conclude with the implementation of an upgrade of the Wi-Fi infrastructure for the Reyers site of the RTBF, a full design of the Wi-Fi network was completed for the 5 GHz band and also for the 2.4 GHz band, reusing the access points locations by working on dual-band. After studying this site, the major issue is the layout of the buildings. Most of the offices are small and close to each other which causes big attenuations in these directions and creating important overlapping in the free zone like the corridors.

Another part of the evolution of the 802.11 standard is the future predictions that can be made about it. New wireless technologies concepts arise every year, promising higher throughputs. So how can the Wi-Fi compete?

With the soon arriving of the 5G, the Wi-Fi’s utility is discussed. With the Li-Fi technology, the whole frequencies are reviewed, involving new concepts. Still, the 802.11 technology is still the most used wireless technology to access the Internet. It allows secured and private Internet access in a relatively large range. The actual technology is still adapted to the society use and a soon arriving of the 802.11ax standard is ensuring the adaptation of the Wi-Fi through some year by announcing data rates of around 4.8 Gbps.

The occasion of predicting about the 802.11 standard future was possible in this project. The RTBF is willing to construct a new building, by 2022. A theorical study of the Wi-Fi network have been completed, allowing to propose a range of access points needed to cover the whole building. Additionally, with the purpose of completing the theorical study, predictions about the characteristics of the end-point Wi-Fi modules and access points were discussed.

The material attenuations were decided based on the sparsely information given by the staff. Still, some conclusion, grounded on the material attenuations measurements done on the actual building, have led to define the losses due to different type of obstruction. Among with the characteristics of the hardware predicted, the theorical calculations will be leaded.

Since there was an important difference in the results of the distance of coverage calculated and in reality, and because of the lack of information on the new building construction materials, it has been chosen that the number of access points needed to ensure a full Wi-Fi coverage will vary within a range. The limits of this range will be defined by two cases, depending on the value given to the probability of signal strength. The worst case corresponds to a probability of 70% with a higher amount of access points needed and the best case to a probability of 50% with a lower amount of access points.

Lastly, a design of a fully covered Wi-Fi network has been completed, for both the worst case and the best case, at a frequency of 5 GHz. The number of access points needed calculated vary between 261 (best case) and 423 (worst case).

To conclude, when implementing a wireless network, it is primordial to understand the different properties of radiowaves and radiocommunication, since these characteristics can imply a well-functioning, reliable and robust network if configured properly, but also have devastating effect on the network if arranged other ways. Another aspect that must be considered is the importance of comparing the theorical calculations with real measurement, to avoid completely unscaled and non-functionable network. The last point to highlight is the importance of the realization of a proper site-survey to allow to characterize the locations and performance needs of the network. With a good understanding and configuring of these aspects, it is possible to implement a well-functioning, performant and reliable Wi-Fi network. It is essential to have a successfully implemented Wi-Fi network to be able to provide the best wireless experience.

Glossary of Abbreviations

4G/LTE 4^{th} Generation/Long Term Evolution
5G 5^{th} Generation

µs Microseconds

AM Amplitude Modulation
AP Access Point

BLE Bluetooth Low Energy
BPSK Binary Phase-Shift Keying
BYOD Bring Your Own Device

CCK Complementary Code Keying

dB Decibel

dBi Decibel isotropic

dBm Decibel relative to 1 milliwatt

DL-MU-MIMO Downlink Multiple-User Multiple-Input Multiple-Output
DSSS Direct-Sequence Spread Spectrum

FCC Federal Communications Commission
FM Frequency Modulation

GHz Giga Hertz
GI Guard Interval

HEW High-Efficiency Wireless Local Area Network
HT-OFDM High Throughput Orthogonal Frequency Division Multiplexing

ICT Information and Communication Technology
IEEE Institute of Electrical and Electronics Engineers
IoT Internet of Things
IP Internet Protocol
ISI Inter Symbol Interference
ISM Industrial, Scientific and Medical
IT Industry and Technologies
IUT International Union of Telecommunications
IUT-R International Union of Telecommunications – Radio Telecommunications sector

kHz Kilo Hertz

LAN Local Area Network
LED Light Emitting Diode
Li-Fi Light Fidelity
LOS Line-of-Sight

M2M Machine to Machine
MCS Modulation Coding Schemes
MHz Mega Hertz
MIMO Multiple-Input Multiple-Ouput
MISO Multiple-Input Single-Output
MU-MIMO Multiple-User Multiple-Input Multiple-Output

NLOS Non-Line-of-Sight

OFDM Orthogonal Frequency Division Multiplexing
OFDMA Orthogonal Frequency Division Multiplexing Access

PDA Personal Digital Asistente

QAM Quadrature Amplitude Modulation
QPSK Quadrature Phase-Shift Keying

RF Radio Frequency
RGB Red Green Blue
RSSI Received Signal Strength Indication
RTBF French-speaking Belgian Radio and Television
RX Receiver

SIMO Single-Input Multiple-Output
SINR Signal-to-Interference and Noise Ratio
SNR Signal-to-Noise Ratio
SISO Single-Input Single-Output
SS Spatiam Stream
SU-MIMO Single-User Multiple-Input Multiple-Output

THz Tera Hertz
TX Transmitor
TWT Target Wakeup Time

U.S. United States of America

VLC Visible Light Communication

Wi-Fi Wireless-Fidelity
WLAN Wireless Local Area Network
WPA2 Wireless-Fidelity Protected Access

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Memory

1. Introduction to the Project

This End-of-Grade Project was achieved within the company RTBF (Francophone Belgian Radio-Television), an autonomous public company with a cultural character that is active in television, radio, Internet and social networks. The RTBF employs 2000 workers in 5 locations. The main goal of this project is to create an improved implementation of the Wi-Fi network currently used in the Reyers site (1000 workers) of the RTBF regarding the existing issues.

The company will replace its main building in the year 2020. This new building will be more automated and will require the proper integration of new technologies. Another goal will be to propose technologies for this new "intelligent" building and implement a theorical study of the coverage for a new Wi-Fi network in that building.

This project is going to approach the 802.11[1] technology in different aspects. If we remember, in the early 2000's, what a mobile phone looked like; it was a device that could send and receive messages, make calls and play fairly basic games. Some parts of the world already had wired Internet access home. Wi-Fi was barely a thing, since the first 802.11 standards were just released.

The number of devices connected to the Internet increased from over 350 million in 2000 to over 4000 million in 2017 [2]. How infrastructures and standards have managed to adapt to the number of devices connected to the Internet growing so fast?

Wi-Fi is the most used technology that connects devices wirelessly to a private network to access the Internet. Billions of users use it in different environments such as work, home and public places (station, airport, …). In order to allow users, more and more numerous, to enjoy a more rewarding experience, the 802.11 standard evolve allowing to achieve wireless high-speed transfers. In addition to the number of personal devices, this technology allows more devices to be connected implying new innovations such as connected homes and workplaces and process and operation automation.

In order to be able to implement a Wi-Fi network, it is necessary to understand what are the technologies involved in the evolution of this standard. For this reason, part of this project will be dedicated to the explanation of the concepts used in the implementation of these technologies.

The realization of the implementation of a Wi-Fi network takes several aspects into account. On one hand, a purely theorical part will clarify the necessary calculations and assumptions by explaining and justifying them [3][4]. On the other hand, no prediction is more accurate than measurements in the place itself. This is why a site survey has been carried out, which has modified certain parameters of the theorical calculations. Finally, a design of an implementation of the Wi-Fi network was created based on the plans of the building.

The last part of this project concerns the implementation of a Wi-Fi network for a new "smart" building. For this implementation, some new or future technologies will be explained to study their possible integration in this new network. Finally, an approximate theorical study will be done on the coverage of a Wi-Fi network for this new building. This study will contain predictive assumption for the network parameters and characteristics and a design based on the plans of the new building. From the design realized, an amount of access points needed for the new building will be conclude.

2. Introduction to Wi-Fi

The beginnings of the Wi-Fi wireless communication system go back to the year 1971 with ALOHAnet connecting the Hawaiian Islands with a UHF wireless packet network. Since then, the number of devices connected to the Internet continues to increase, with today more than 9 billion devices connected to the Internet including the handheld or personal mobile-ready devices (smartphones, tablets, …) and M2M connections (medical applications, GPS systems, …) [5].

Figure 1 shows the increase of connected devices from 2016 till today and the prediction from now to 2021.

Figure 1 Global Mobile Devices and Connections Growth from 2016 to 2021 [5]

From Figure 1, it is possible to see the incredible increase of devices connected to the Internet. Due to the introduction of the IoT (Internet of Things), "smart" buildings, cities, automobiles, etc. will further increase the number of devices in the near future that will be connected to the Internet.

To better understand today's Wi-Fi systems, an introduction will review its history and the different standards that exists. Also, the main features of wireless systems will be explained for a better comprehend of the way the data is sent over wireless radio waves.

2.1. Introduction to the Standard 802.11

The 802.11 standard [1] is an international standard that allows to create high-speed wireless local networks. Wi-Fi allows to connect devices to a broadband link. It is a technology that has revolutionized the way to connect devices wirelessly.

A Wi-Fi network is actually a network that meets the 802.11 standard.

2.1.1. History

The first version of the 802.11 standard was released in 1997 with, as the primary driver, code barre scanning. No one thought that two decades later, it would be the primary access method into a network.

In 1999, Wi-Fi made its debut with the 802.11a standard aimed for business and the 802.11b standard intended for individuals. To better imagine the impact of wireless devices, at that time, for an enterprise of 100 employees, there was only one or two devices connected since most of the devices were desktop machines or plug-in devices.

The next 802.11 standard, 802.11g, appeared in 2003. This standard associates the 802.11a and 802.11b standards but is only compatible with the norm 802.11b since it uses the same frequency band. At that time, for an enterprise of 100 employees, there was around 5-10 wireless devices connected to the Internet. The increase of connected devices was due to the introduction of the Intel Centrino chip that allowed laptop to have an on-board Wi-Fi module, allowing those devices to communicate through the 802.11 standard.

Until this point, the devices were all single radio devices due to the fact that the battery technology did not allow to work with two radios on different bands. Since then, the technology has allowed to have batteries with much more time of life and allowed the introduction of devices with two radios that allows to transmit on two different bands.

In 2007, 802.11n is proposed in order to improve the network performance of the previous standards. 802.11n is built based on previous standards, adding technologies such MIMO (Multiple-Input Multiple Output) and channel bonding. At that time, for an enterprise of 100 employees, there was around 25 wireless devices connected to the Internet. This standard allows high speed and a longer coverage range over the 2.4 GHz and the 5 GHz bands.

In the same year, 802.11i is published. It is implemented as WPA2 (Wi-Fi Protected Access II). This standard specifies security mechanisms for wireless network.

In 2009 begins more significant increase of Wi-Fi connected devices with the introduction of the Iphone 3G and other smartphones. In 2010, for an enterprise of 100 employees, there was around 150 wireless devices connected to the Internet, more than one device per employee.

Moreover, it was the period of BYOD (Bring Your Own Device) where many employees could bring their own device in the office, adding more load to the wireless systems. The problem encountered then was that all the Wi-Fi network were designed for six times less devices. Those networks were no longer robust enough to allows that much traffic. There has been a high impact on how industry is changing and on how we are using the infrastructure.

In 2013, the 802.11ac phase 1 (wave 1) standard was published. The changes compared to its predecessor are: wider channels, more spatial streams and the addition of the Multi-User MIMO (MU-MIMO) antenna system. On that year, for an enterprise of 100 employees, there was more than 200 wireless devices connected to the Internet. Almost every employee had its own laptop and smartphone connected to the Wi-Fi network.

In 2015, the 802.11ac phase 2 (wave 2) standard was released. It added the beamforming technology which allows to direct the communication directly to the user.

Today, for an enterprise of 100 employees, there is over 300 wireless devices to the Internet. Those devices are mostly composed of laptops, tablets and smartphones with over 85 applications installed on each smartphone.

2.1.2. Standards

The Table 1 reflects the evolution of the 802.11 standards, with their corresponding operating frequency band, bandwidths available, used modulation and antenna technologies and maximum theorical data rate.

802.11 Standards						
Release Date	Standard	Frequency Band (GHz)	Bandwidth (MHz)	Modulation	Advanced Antenna Technologies	Maximum Theorical Data Rate
1997	802.11	2.4 GHz	20 MHz	DSSS, FHSS	N/A	2 Mbps
1999	802.11b	2.4 GHz	20 MHz	DSSS	N/A	11 Mbps
1999	802.11a	5 GHz	20 MHz	OFDM	N/A	54 Mbps
2003	802.11g	2.4 GHz	20 MHz	DSSS, OFDM	N/A	542 Mbps
2009	802.11n	2.4 GHz, 5 GHz	20 MHz, 40 MHz	OFDM	MIMO, up to 4 spatial streams	600 Mbps
2013	802.11ac	5 GHz	40 MHz, 80 MHz	OFDM	MIMO, MU-MIMO, up to 8 spatial streams	6.93 Gbps

Table 1 Evolution of 802.11 Standards [6]

NOTE: The maximum data rates shown in Table 1 is a theorical throughput value that depends on the number of spatial streams. The data rate practically measured are lower than the theorical maximum data rate since only a few devices allows to operate with the maximal number of spatial streams.

2.1.2.1. 802.11a

802.11a standard operates in the 5 GHz band. Its architecture is based on two types of devices: the APs (Access Points) and the wireless clients that can be mobile devices as laptop, PDAs, fixed devices as desktops and workstations equipped with a wireless network interface.

This standard uses an OFDM (Orthogonal Frequency Division Multiplexing) modulation with 52 subcarriers, 48 of them are used for the data transmission and 4 of them for pilot tasks. Each subcarrier can be modulated by BPSK (Binary Phase Shift Keying), QPSK (Quaternary Phase Shift Keying), 16- or 64-QAM (Quadrature Amplitude Modulation).

802.11a provides 12 non-overlapping channels. As it uses the 5 GHz band, the signal has less interference than other 802.11 standards operating in the 2.4 GHz band.

2.1.2.2. 802.11b

802.11b operates at 2,4 GHz. This standard can be used in point-to-multipoint or point-to-point topology with links over distances proportional to the features of the antennas and output power.

This standard data is encoded using DSSS (Direct Sequence Spear Spectrum Signal). This technology uses CCK (Complementary Code Keying) and QPSK modulation.

2.1.2.3. 802.11g

802.11g operates at 2.4 GHz and is compatible with the 802.11b standard. It uses 52 subcarriers. In this standard there is a speed decrease accordingly to the signal quality.

The modulation scheme is OFDM modulation.

802.11g may seem to be the competence of 802.11a but most products include both technologies because they are complementary.

2.1.2.4. 802.11n

802.11n operates at 2.4 GHz and 5 GHz. On the 5 GHz band, it introduces a bounding channel (double the bandwidth). This bounding channel allows to work with 20-MHz and 40-MHz bandwidth. This standard brings the MIMO technology that allows to exploit simultaneously several streams. 802.11n can, in theory, reach four by four MIMO (four transmitters and four receiver antennas).

802.11n standard uses an OFDM modulation.

2.1.2.5. 802.11ac

802.11ac is a transformational WLAN (Wireless Local Area Network) technology that represents a significant performance increase over its highly successful predecessor, 802.11n. 802.11n provided the wireless connectivity speeds that businesses needed to embrace Wi-Fi in their day-to-day operations and let workers begin using wireless as their primary network medium of choice.

802.11ac is coming to market in two releases: Wave 1 and Wave 2.

2.1.2.6. 802.11ac Wave 1

The 802.11ac first release allows to increase the throughput by improving each transmission techniques used:

- 802.11ac only operates in the 5 GHz band, APs switch to 802.11n for the 2.4 GHz band.
- Modulation changes from 64-QAM to 256-QAM, increasing the bandwidth by 25%,
- New channel width of 80-MHz, doubling the bandwidth compared to the four maximum streams of 802.11n.
- Potential to up to three spatial streams.
- Beamforming that allows APs to direct waves to terminals and improve the performance.

2.1.2.7. 802.11ac Wave 2

The 802.11ac wave 2 is a superset of 802.11ac wave 1. It supports all data rates of 802.11ac wave 1 with the addition of some techniques:

- New channel width of 160-MHz, quadrupling the bandwidth compared to the four maximum streams of 802.11n. Operating at 160-MHz requires a clear channel and may mean that most APs will continue to use both 80-MHz and 40-MHz, even though the wave 2 is able to switch between them.

- MU-MIMO support which allows APs to communicate with multiple terminals simultaneously rather than in turn and must be supported by the AP and the client. The multi-user format is meant to boost the user capacity. The receiver device must allow to use this technology by implementing multiple antennas.
- Potential to up to four spatial streams. This would require both the APs and the clients to add an additional fourth antenna.

2.2. Characteristics

The Wi-Fi characteristics are mainly its operating frequencies and its modulation and codification methods. Those aspects are relevant in the throughput and capacity of the network and are discussed below.

2.2.1. Frequency bands

In the mid-1980s, the U.S. Federal Communications Commission (FCC) modified Part 15 of the radio spectrum regulation, which governs unlicensed devices [7]. The modification authorized wireless network products to operate in the industrial, scientific, and medical (ISM) bands using spread spectrum modulation. The ISM frequencies are located in various bands, including three different bands, located at 900 MHz, 2.4 GHz, and 5 GHz [8].

Each set of bands has different characteristics. The lower frequencies exhibit better range, but with limited bandwidth and hence lower data rates. The higher frequencies have less range, are subject to greater attenuation from solid objects but hence higher throughputs.

Wi-Fi operates in "unlicensed" frequency bands so it does not show up in the overall spectrum allocation as a service. It has beginnings in the ISM band where it was not desirable or profitable to license such short-range devices. The first frequencies for Wi-Fi use was in the 2.4 GHz range. As Wi-Fi popularity and usage increased the FCC allocated additional spectrum in the 5 GHz band where there is more bandwidth and mechanisms in place to co-exist with other services such as radars.

2.2.1.1. Interferences

Radio frequency interference can lead to disastrous problems on WLAN deployments. The perils of interfering signals from external RF sources are often the culprit. As a result, it is important to be fully aware of RF interference impacts and avoidance techniques. The 2.4 GHz band suffers from much more interferences than the 5 GHz band.

2.2.1.1.1. Sources

As 802.11 devices operate in the unlicensed bands, this makes it available for anyone to use. With 2.4 GHz WLANs, there are several sources of interfering signals, including microwave ovens, cordless phones, Bluetooth enabled devices, and neighboring WLANs:

- The most damaging of these are 2.4 GHz cordless phones that people use extensively in homes and businesses. If one of these phones is in use within the same room as a 2.4GHz WLAN, then expect poor WLAN performance when the phones are in operation.

- Microwave operating within 3 meters or so of an AP may also cause its performance to drop. Of course, the oven must be operating for the interference to occur, which may not happen very often depending on the usage of the oven.

- Bluetooth enabled devices, such as laptops and PDAs, will cause performance degradations if operating in close proximately to 802.11 stations, especially if the 802.11 station is relatively far (i.e., low signal levels) from the station that it is communicating with.
- Other WLANs, such as the neighbor's WLAN, can cause interference unless you coordinate the selection of 2.4 GHz channels.

2.2.1.1.2. Impact

RF interference involves the presence of unwanted, interfering RF signals that disrupt normal wireless operations. Each 802.11 station only transmits packets when there is no other station transmitting. If another station happens to be sending a packet, all the other stations will wait until the medium is free. Because of the 802.11 medium access protocol, an interfering RF signal of sufficient amplitude and frequency can appear as a bogus 802.11 station transmitting a packet. This causes legitimate 802.11 stations to wait for indefinite periods of time (until the interfering signal goes away) before attempting to access the medium.

To make matters worse, RF interference are not tolerated by the 802.11 protocols, so the interfering signal may start abruptly while a legitimate 802.11 station is in the process of transmitting a packet. If this occurs, the destination station will receive the packet with errors and not reply to the source station with an acknowledgement. In return, the source station will attempt retransmitting the packet, adding overhead on the network.

Of course, this all leads to network latency and unhappy users. In some causes, 802.11 protocols will attempt to continue operation in the presence of RF interference by automatically switching to a lower data rate, which also slows the use of wireless applications. The worst case, which is fairly uncommon, is that the 802.11 stations will hold off until the interfering signal goes completely away, which could be minutes, hours, or days.

2.2.2. Channels

Similar to channels on a traditional television, each Wi-Fi channel is designated by a number that represents a specific radio communication frequency. The two bands used by the 802.11 standards are the 2.4 GHz band and the 5 GHz band.

2.2.2.1. 2,4 GHz band

The 2.4 GHz band contains 14 channels which are evenly spaced at 5 MHz intervals, between 2.4 GHz and 2.5 GHz.

Because each 2.4 GHz Wi-Fi channel requires a signaling band of 22 MHz wide, radio frequencies of neighboring channels numbers significantly overlap each other. For this reason, only non-overlapping channels can be used for transmissions. Those non-overlapping channels are channel 1, channel 6 and channel 11. The Figure 2 illustrate the 2.4 GHz spectrum where the overlapping of channels and the three non-overlapping are shown.

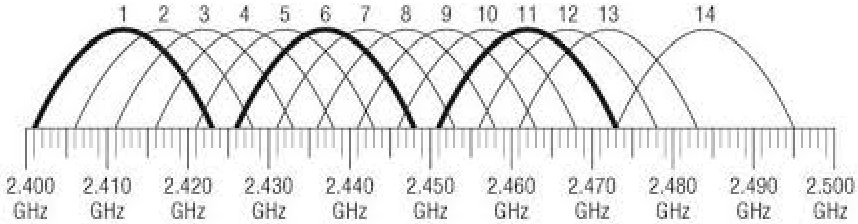

Figure 2 The 2.4 GHz Band [9]

2.2.2.2. *5 GHz band*

The 5 GHz band offers significantly more channels than does the 2.4 GHz band. To avoid issues with overlapping frequencies, 5 GHz equipment restricts available channels to a certain lower number to obtain only non-overlapping channels. This is similar to how AM/FM radio stations, within a local area, keep some separation between each other on the bands.

The 25 non-overlapping channels in the 5 GHz band are shown in the Figure 3:

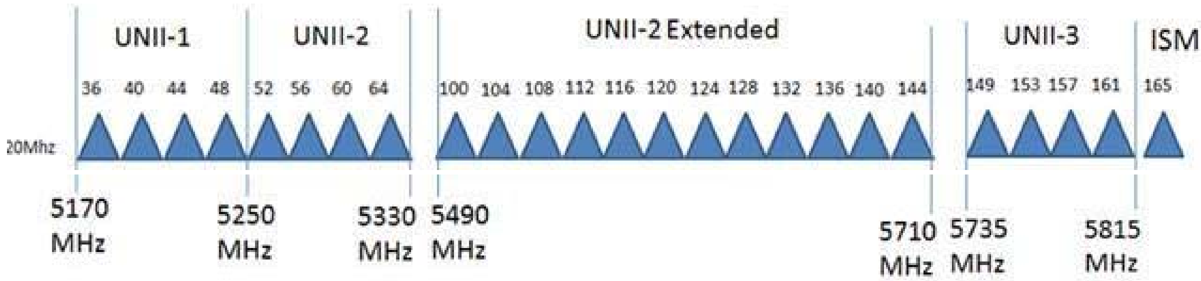

Figure 3 The 5 GHz Band 20 MHz Bandwidth [10]

The 5 GHz band included the frequencies from 5170 MHz to 5815 MHz, allowing to have more non-overlapping channels than the 2,4 GHz band due to the wideness of the spectrum available in this band.

The 802.11b standard is the only Wi-Fi standard that uses DSSS modulation only. Because of this characteristic, it is the only standard that uses 22 MHz wide channels uniquely. The 802.11g standard can either use DSSS or OFDM modulation, so it cas either use the 22 MHz wide channels (if modulating with DSSS) or 20 MHz wide channels (if modulating with OFDM). Both the 802.11b and 802.11g standards operate at 2.4 GHz, which obligates the channels of the 2.4 GHz band to be 22 MHz wide.

All the other 802.11 standards (802.11a/n/ac) use the OFDM modulation, and will use 20 MHz wide channels.

2.2.3. Channel Bonding

The channel width is the width of the spectrum used for the transmission, being the maximum 160-MHz. Channel bonding is a mechanism where neighboring 20-MHz (smaller bandwidth) channels are bonded together to form a larger channel. A 40-MHz channel is two aggregated 20-MHz channels. It takes advantage of the reserved channel space through bonding to gain more than double the data rate of two 20-MHz channels. By increasing the channel width, the data capacity of the transmission increases.

The wider the channel is, the more bandwidth and data rate will have the transmission and the less range will have the AP.

In the 2.4 GHz band, it is clear that only one 40-MHz channel can be bonded, taking the whole 2,4 GHz spectrum. At that frequency band, channel bonding is only possible for burst mode because its bandwidth is already limited by the number of channels available.

The channel bonding mechanism is mainly used in the 5 GHz band, where there are enough channels to achieve the WLAN goals using bonded channel plan to meet throughput goals. In the Figure 4, the different possibilities of the channel bonding for the 5 GHz band are shown.

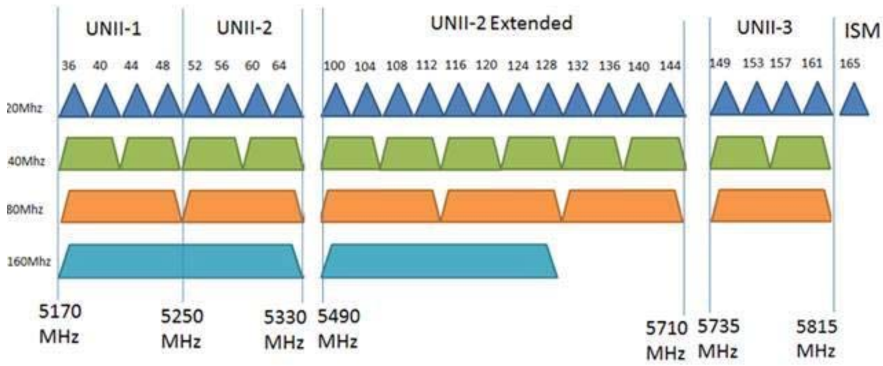

Figure 4 The 5 GHz band 20 MHz, 40 MHz, 80 MHz and 160 MHz Bandwidth [10]

From the Figure 4, the 25 20-MHz non-overlapping channels can be bonded into 12 40-MHz non-overlapping channels, 6 80-MHz non-overlapping channels or 2 160-MHz non-overlapping channels.

When using bonded channel, 802.11n takes advantage of the fact that each 20-MHz channel has a small amount of the channel that is reserved at the top and bottom, to reduce interference in those adjacent channels.

When using 40-MHz channels, the top of the lower channel and the bottom of the upper channel (shown in Figure 5) do not have to be reserved to avoid interference. These small parts of the channel can now be used to carry information. By using the two 20-MHz channel the communication is more efficient.

802.11n achieves slightly more than doubling the data rate when moving from 20-MHz to 40-MHz channels.

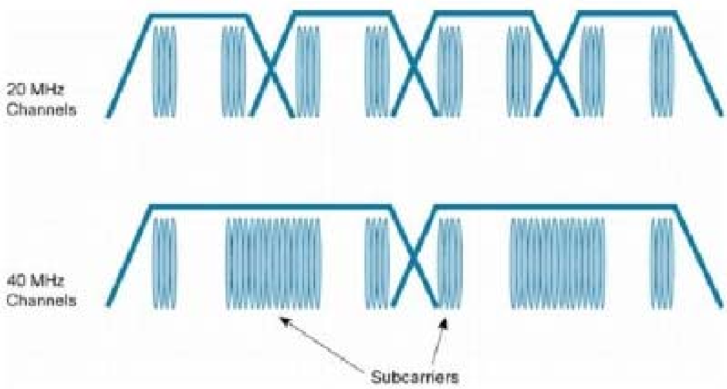

Figure 5 Channel Bonding of 20 MHz Channels Into an 40 MHz Channel [11]

Channel bounding in 2.4 GHz should be avoided in enterprise deployments because it would use the whole 2.4 GHz spectrum. For this reason, it should only be used in the 5 GHz band as the spectrum is much wider, and there are enough non-overlapping channels to bond them without using the whole spectrum for a transmission.

2.2.4. Modulation and Coding Schemes (MCS)

Beginning with the introduction of IEEE 802.11n [12], modulation and coding schemes (MCS) are used to determine the data rate of a wireless connection using high-throughput orthogonal frequency division multiplexing (HT-OFDM). The MCS Index is the unique reference given to a combination of number of spatial streams, plus modulation type, plus the coding rate (the coding rate is an indication of how much of the data stream is actually being used to transmit usable data).

Pre-802.11n systems using OFDM had defined data rates between 6 and 54 Mbps based on what type of modulation and coding were used. HT-OFDM uses other parameters, such as channel size, number of spatial streams, coding method, modulation technique, and guard interval. Each MCS is based on a combination of these parameters. There are 77 different types of MCS for both 20 and 40 MHz channels, eight of which are mandatory for 20 MHz channels, and correspond to mandatory basic data rates.

802.11ac/n systems determine the proper MCS to use based on channel conditions as discerned from feedback from the receiver. The MCS is negotiated during communication and serves to strike a balance between maximum data rate and maximum acceptable error rate.

2.2.4.1. Guard Interval (GI)

When data is encoded by any of the various methods available, bits are converted into symbols, which are then modulated onto the carrier signal for transmission. A typical symbol has a duration of 4 µs [13].

A GI is a period of time between symbol transmission that allows reflections (from multipath) from the previous data transmission to settle before transmitting a new symbol. The signal content inside the GI, called Inter-Symbol Interference (ISI), is rejected by receivers. To avoid the problem of ISI, a guard interval of 800 nanoseconds is inserted between each symbol (the symbol is actually 3,2 µs and the GI is 0,8 µs).

ISI occurs because of the multipath phenomenon; symbols that reach the receiver at different time, called the delay spread, can interfere with and corrupt another, resulting in frequent retransmissions. GI of 800 nanoseconds is chosen because the maximum multipath echo time is typically considered to be 800 nanoseconds in an indoor environment. 800 nanoseconds is the time that takes a radio wave to travel 240 meters at the light speed, allowing the difference in the travelled distance (between the shortest and the longest distance travelled) to not exceed the 240 meters and to avoid the ISI. Outdoor GIs are typically higher.

The timeframe of the symbols and guard intervals is shown in Figure 6, on the left's figure using a correct GI and on the right figure using a GI that is too short.

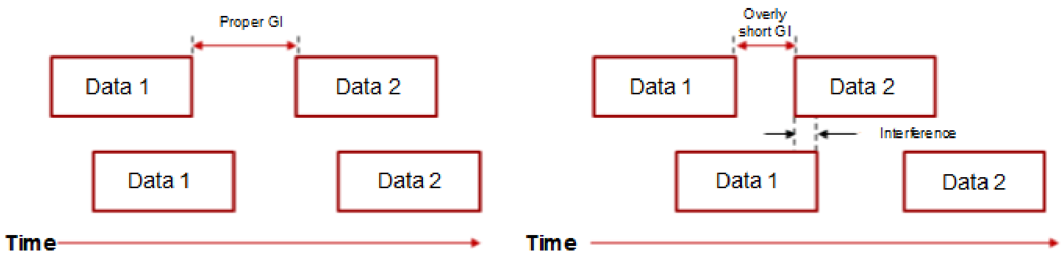

Figure 6 Correct and Incorrect Guard Interval [14]

Using a smaller GI will increase the throughput but could also compromise the system reliability. A shorter GI corresponds to a shorter intersymbol time and ISI can occur. Choosing a GI that is too short means that ISI will increase, and throughput will decrease. Choosing a GI too long means decreased overhead due to unnecessary idle time on the wireless medium. Choosing a proper GI time period is crucial to optimizing throughput.

802.11ac/n systems use an 800 nanosecond GI but there is an option to use a 400 nanosecond GI.

In Table 2, the MCS Index for 802.11n standard is shown, for one and two spatial streams and for 20-MHz and 40-MHz wide signals. Table 2 is based on the data found in the datasheet of the Cisco 2700 series AP under the 802.11n at 2.4 GHz data rates supported that can be found in the Annex 1.

MCS Index	Modulation	Spatial Streams	Data rates			
			20 MHZ		40 MHz	
			400 ns	800 ns	400 ns	800 ns
0	BPSK	1	6,5 Mbps	7,2 Mbps	13,5 Mbps	15 Mbps
1	QPSK	1	13 Mbps	14,4 Mbps	27 Mbps	30 Mbps
2	QPSK	1	19,5 Mbps	21,7 Mbps	40,5 Mbps	45 Mbps
3	16-QAM	1	26 Mbps	28,9 Mbps	54 Mbps	60 Mbps
4	16-QAM	1	39 Mbps	43,3 Mbps	81 Mbps	90 Mbps
5	64-QAM	1	52 Mbps	57,8 Mbps	108 Mbps	120 Mbps
6	64-QAM	1	58,5 Mbps	65 Mbps	121,5 Mbps	135 Mbps
7	64-QAM	1	65 Mbps	72,2 Mbps	135 Mbps	150 Mbps
8	BPSK	2	13 Mbps	14,4 Mbps	27 Mbps	30 Mbps
9	QPSK	2	26 Mbps	28,9 Mbps	54 Mbps	60 Mbps
10	QPSK	2	39 Mbps	43,3 Mbps	81 Mbps	90 Mbps
11	16-QAM	2	52 Mbps	57,8 Mbps	108 Mbps	120 Mbps
12	16-QAM	2	78 Mbps	86,7 Mbps	162 Mbps	180 Mbps
13	64-QAM	2	104 Mbps	115,6 Mbps	216 Mbps	240 Mbps
14	64-QAM	2	117 Mbps	130 Mbps	243 Mbps	270 Mbps
15	64-QAM	2	130 Mbps	144,4 Mbps	270 Mbps	300 Mbps

Table 2 Cisco 2700 Series Access Points Data Rates of 802.11n Standard at 2.4 GHz [15]

In Table 3, the MCS Index for 802.11ac standard is shown, for one and two spatial streams and for 20-MHz, 40-MHz and 80-MHz wide signals. Table 3 is based on the data found in the datasheet of the Cisco 200 series AP under the 802.11ac at 5 GHz data rates supported that can be found in the Annex 2.

MCS Index	Modulation	Spatial Streams	Data rates					
			20 MHZ		40 MHz		80 MHz	
			800 ns	400 ns	800 ns	400 ns	800 ns	400 ns
0	BPSK	1	6,5 Mbps	7,2 Mbps	13,5 Mbps	15 Mbps	29,3 Mbps	32,5 Mbps
1	QPSK	1	13 Mbps	14,4 Mbps	27 Mbps	30 Mbps	58,5 Mbps	65 Mbps
2	QPSK	1	19,5 Mbps	21,7 Mbps	40,5 Mbps	45 Mbps	87,8 Mbps	97,5 Mbps
3	16-QAM	1	26 Mbps	28,9 Mbps	54 Mbps	60 Mbps	117 Mbps	130 Mbps
4	16-QAM	1	39 Mbps	43,3 Mbps	81 Mbps	90 Mbps	175,5 Mbps	195 Mbps
5	64-QAM	1	52 Mbps	57,8 Mbps	108 Mbps	120 Mbps	234 Mbps	260 Mbps
6	64-QAM	1	58,5 Mbps	65 Mbps	121,5 Mbps	135 Mbps	263,3 Mbps	292,5 Mbps
7	64-QAM	1	65 Mbps	72,2 Mbps	135 Mbps	150 Mbps	292,5 Mbps	325 Mbps
8	256-QAM	1	78 Mbps	86,7 Mbps	162 Mbps	180 Mbps	351 Mbps	390 Mbps
9	256-QAM	1	-	-	180 Mbps	200 Mbps	390 Mbps	433,3 Mbps
0	BPSK	2	13 Mbps	14,4 Mbps	27 Mbps	30 Mbps	58,5 Mbps	65 Mbps
1	QPSK	2	26 Mbps	28,9 Mbps	54 Mbps	60 Mbps	117 Mbps	130 Mbps
2	QPSK	2	39 Mbps	43,3 Mbps	81 Mbps	90 Mbps	175,5 Mbps	195 Mbps
3	16-QAM	2	52 Mbps	57,8 Mbps	108 Mbps	120 Mbps	234 Mbps	260 Mbps
4	16-QAM	2	78 Mbps	86,7 Mbps	162 Mbps	180 Mbps	351 Mbps	390 Mbps
5	16-QAM	2	104 Mbps	115,6 Mbps	216 Mbps	240 Mbps	468 Mbps	520 Mbps
6	64-QAM	3	117 Mbps	130,3 Mbps	243 Mbps	270 Mbps	526,5 Mbps	585 Mbps
7	64-QAM	4	130 Mbps	144,4 Mbps	270 Mbps	300 Mbps	585 Mbps	650 Mbps
8	256-QAM	5	150 Mbps	173,3 Mbps	324 Mbps	360 Mbps	702 Mbps	780 Mbps
9	256-QAM	6	-	-	360 Mbps	400 Mbps	780 Mbps	866,7 Mbps

Table 3 Cisco 2700 Series Access Points Data Rates of 802.11ac Standard at 5 GHz [15]

Choosing a 400 ns GI adds approximately 11% to the achievable data rate over the 800 ns GI. Note the increase in throughput as more spatial streams are brought into play.

2.2.4.2. Modulations

Modulation is the method by which data is communicated through the air. The more complex the modulation, the higher the data rate. More complex modulations require better conditions such as less interference and a good line of sight.

802.11standards can use different digital modulation schemes for data transmission. Environmental factors and protocol will define the scheme selection. Radio frequency waveforms have three basic properties that can be modified in order to transmit digital data over an analog carrier signal: amplitude, frequency and phase. In 802.11 networks, the frequency is a fixed parameter so only the amplitude and phase can be modified in the modulation schemes.

2.2.4.2.1. Phase Shift Keying (PSK)

A PSK modulation is when the phase represents the current position of an oscillating waveform. PSK varies the phase of the current oscillating waveform with reference to an arbitrary position on a reference waveform. Digital data is encoded by shifting the waveform among a list of pre-determined degree offsets from the expected position.

BPSK

BPSK modulation is a phase modulation by binary digital signal. The carrier has a constant amplitude and a phase at the origin that can take two values, 0 and π. There is a carrier wave and the data are transmitted by another wave working at different phases to the carrier wave to denote differing binary codes. This allows more than one bit to be transferred at a time and increases the effective bandwidth.

By using BPSK, there is two phases around the carrier wave and each phase denote one bit. The modulation pattern is shown in the Figure 7.

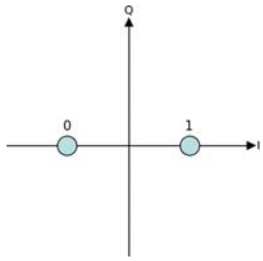

Figure 7 BPSK Modulation Scheme [16]

QPSK

By using QPSK, there are four phases around the carrier wave and each phase denote a bit-pair, as shown in the modulation pattern in the Figure 8. Those four phases are $\pi/4$, $3\pi/4$, $5\pi/4$ and $7\pi/4$.

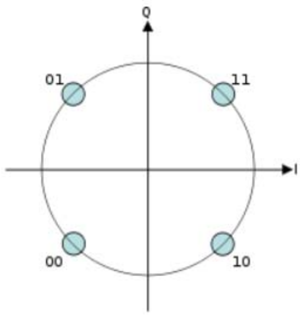

Figure 8 QPSK Modulation Scheme [17]

By using more phases, the number of bit represented increases by each phase difference but at the cost of increasing transmitter and receiver complexity.

2.2.4.2.2. QAM (Quadrature Amplitude Modulation)

QAM modulations are an extension of PSK modulations; the carrier sees its amplitude and/or phase shifting with each change of symbols. Depending on the number of phases and amplitude possible, the number of bits sent changes.

The modulation of the 8-QAM is shown in Figure 9.

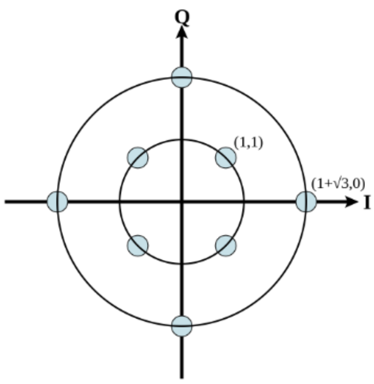

Figure 9 8-QAM Modulation Scheme [18]

As higher order modulation techniques increase data throughput by encoding more bits per-baud, it also reduces resistance to noise and the air time. That is the reason why Wi-Fi clients will data-rate shift to lower data rates in the presence of interference, noise or data corruption, possibly despite a strong link signal.

2.2.4.3. Codifications

The Wi-Fi networks use efficient codification techniques. The three techniques used are CCK (Complementary Code Keying), DSSS (Direct-Sequence Spread Spectrum) and OFDM, depending on the 802.11 standard operating.

2.2.4.3.1. Direct-Sequence Spread Spectrum (DSSS)

DSSS is a method of spreading out a serial data stream across a range of frequencies which make up a single "channel". The channels are referenced by their primary carrier frequency at the center of the channel and each channel is separated by 5 MHz. DSSS is designed to be used at low power but spanning a much larger frequency range (bandwidth) than is required to encode the data versus a narrowband transmitter (such as a radio or television transmitter). By spreading the data out over a larger range of frequencies, spread spectrum technologies such as DSSS are less susceptible to narrowband interference. Additionally, due to the low power, DSSS is also less likely to cause interference to other RF systems. This is part of the reason why unlicensed frequency use is permitted by the FCC.

Principle

The principle of the DSSS modulation is to operate an exclusive OR on two signals, the useful signal and the binary code. The useful signal is the signal carrying the data to be send in binary form (1s and 0s). Each bit of the useful signal lasts a period of T_S, which implies that the useful signal is sent at a rate of $1/T_S$. The binary code is a pseudo-random bit sequence that is used to encode the data to be sent (the useful signal). Each bit of the binary code sequence lasts a period of T_C. Finally, in order to encode the useful signal, $N_C x T_C$ must be equal to T_S, being $N_C x T_C$ the period of the binary code. This process is illustrated in Figure 10.

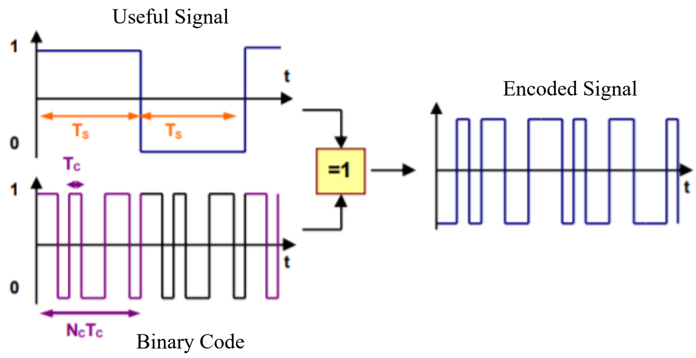

Figure 10 Signal processing of the DSSS Codification [19]

The coded signal has a rate of N_C times greater than the initial signal. The corresponding spectrum is spread in a N_C ratio; the spreading factor is SF = N_C. The spread spectrum is shown in Figure 11.

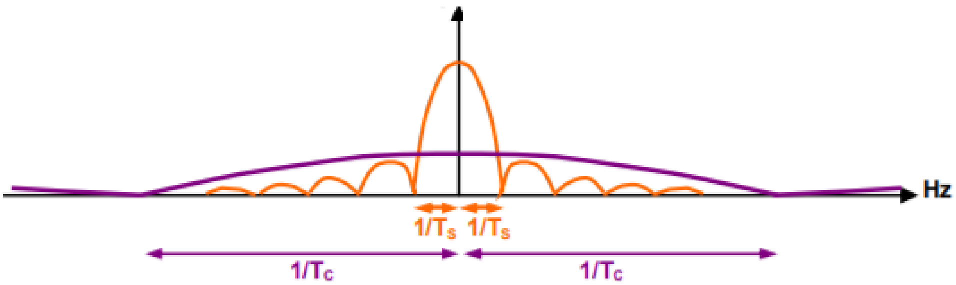

Figure 11 Spectrum of a DSSS Encoded Signal [19]

Several transmitters can coexist on the same frequency band as each of them works with its own binary code.

Depending on the initial signal rate (non-spread) and the Wi-Fi standard, the spread signal then modulates a carrier in BPSK, QPSK or QAM. In the case of multiple carriers, OFDM coding is required.

2.2.4.3.2. Complementary Code Keying (CCK)

CCK is a modulation method used in wireless networks. Complementary codes comprise a pair of equal finite length sequences having the property that the number of pairs of like elements with any given separation in one series is equal to the number of pairs of unlike elements with the same separation in the other. This symmetry is illustrated in Figure 12.

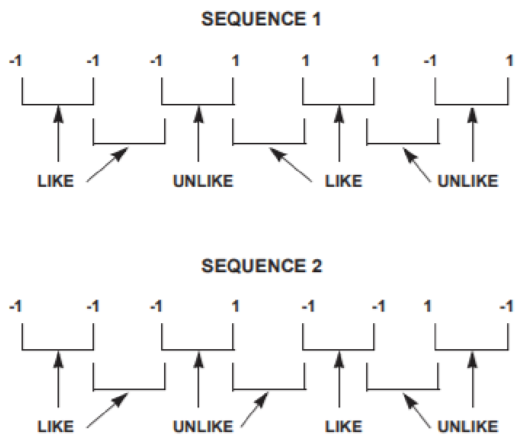

Figure 12 Pair of Equal Finite Length Sequences [20]

The sequence 1 has four pairs of like elements and three pair of unlike elements with a separation of 1, whereas sequence 2 has three pairs of like elements and four pair of unlike elements with a separation of 1.

Table 4 summarize the results of the elements pairing for separations of 1, 2 and 3.

PAIR SEPARATION	SEQUENCE 1		SEQUENCE 2	
	LIKE	UNLIKE	LIKE	UNLIKE
1	4	3	3	4
2	4	3	3	4
3	1	5	5	1

Table 4 Results of Elements Pairing for Sequences 1 and 2 [20]

CCK uses a chipping sequence lookup table, and the chip sequences have been carefully selected to provide optimal transmission characteristics (such as not having long strings of a single value repeating, and overall direct current symmetry).

CCK has a short chipping sequence that means less spreading to obtain a higher data rate but more susceptible to narrowband interference resulting in a shorter radio transmission range compared to DSSS. Beside shorter chipping sequence, CCK also has more chipping sequences to encore more bits increasing the data rate even further.

2.2.4.3.3. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM consists of multiplexing a set of symbols on a set of orthogonal subcarriers between themselves. This eliminates the effects of intersymbol interference due to the introduction of "cyclic prefix".

In the OFDM system, each tone is orthogonal to the adjacent tones and therefore does not require the frequency guard band needed for direct sequence. This guard band lowers the bandwidth efficiency and wastes up to 50 percent of the available bandwidth. Because OFDM is composed of many narrow-band tones, narrow-band interference degrades only a small portion of the signal, with little or no effect on the remainder of the frequency components.

By using OFDM, it is possible to avoid the transmission of a single broadband signal by transmitting a set of narrowband signals orthogonal to each other, thereby resulting in a more robust multipath propagation.

The concept of OFDM is illustrated in Figure 13, where each sub-carrier, equally spaced with each other in frequency, multiplex sets of symbols over time.

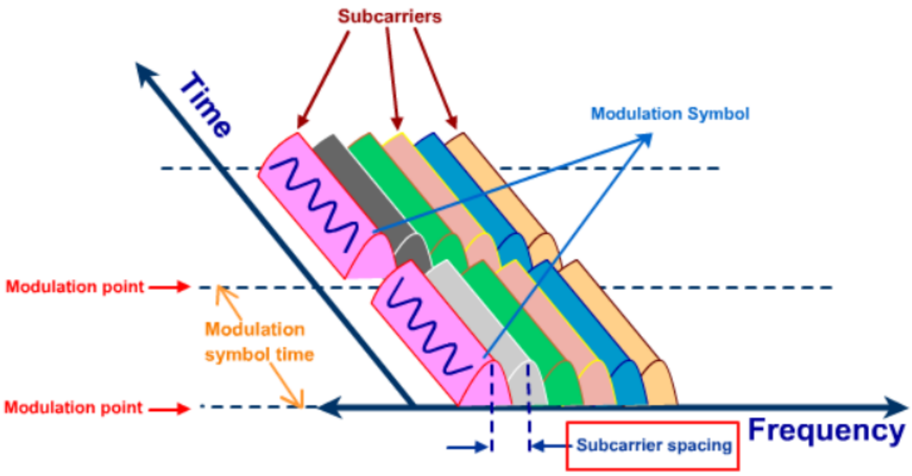

Figure 13 OFDM Coding Depending on Time and Frequency [21]

In 802.11, each 20 MHz channel is composed of 64 subcarriers spaced 312.5 kHz apart. For the 802.11a/g standards, 48 subcarriers are used for data, 4 for pilot and 12 as null subcarriers, whereas in 802.11n/ac standards, 52 subcarriers are used foor data, 4 for pilot and 8 as null. The Figure 14 shows the OFDM carriers for the 802.11a and 802.11g standards in the 2.4 GHz band.

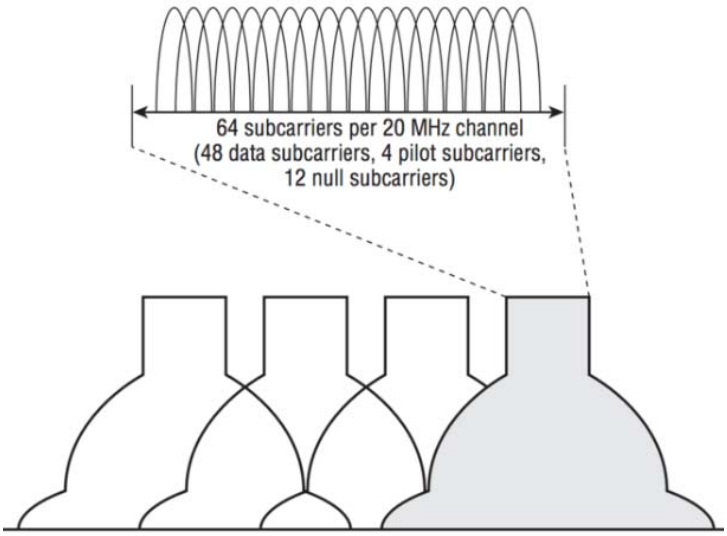

Figure 14 OFDM Subcarriers in 802.11a/g standards [22]

Finally, the modulation and coding used for each 802.11 standard are reflected in Table 5.

Standard	Modulation	Coding
802.11a	BPSK to 256-QAM	OFDM
802.11b	BPSK to 256-QAM	CCK, DSSS
802.11g	BPSK to 256-QAM	DSSS, OFDM
802.11n	BPSK to 256-QAM	OFDM
802.11ac	BPSK to 256-QAM	OFDM

Table 5 Modulation and Coding of Each 802.11 Standard [23]

NOTE: The modulations and coding allowed for each 802.11 Standard shown in Table 5 depend on the radio conditions.

3. Radio Frequency Propagation Indoor

Propagation modeling is vital for the design and development of wireless communications systems.

A wireless system is reach by other problems than wired networks. Those problems are mainly due to the propagation of an electromagnetic signal, such as reflection, and also due to multipath distortion. All the physical modes of the electromagnetic signal propagation from with suffer wireless signals will be explained.

Finally, the different types of antennas are being reviewed, with their corresponding characteristics. Moreover, the proper use and placement will be explained.

3.1. Electromagnetic Signal Propagation

In an indoor environment, the propagated signal will strike on different types of obstacles. The way in which the signal will react depends on the physical and signal properties. The physical properties are the surface's geometry, texture and material composition. Signal properties are the arriving incident angle, orientation, and wavelength.

The propagated electromagnetic signal in the indoor environment can suffer from three primary physical modes: reflection, diffraction, and scattering.

3.1.1. Reflection

Refraction is the bending of the wireless signal as it goes through a medium of higher density than its origin. The wireless signal changes its direction because it bounces off objects. Perfect conductors will reflect all of the signal. Other materials will reflect part of the incident energy and transmit the rest. The exact amount of transmission and reflection also dependent on the angle of incidence, material thickness and dielectric properties. Major contributors to reflection are walls, floors, ceilings and furniture.

Figure 155 shows a reflection reaction of an incoming signal on an obstacle. It can be seen from Figure 15 that the incoming signal result in three signals after striking the obstacle. The reflected signal does not pass through the obstacle and it is the incoming signal bending. The two partials signals (from the incoming and reflected signals) pass through the medium with a lower strength.

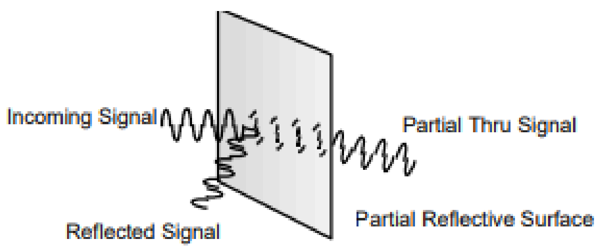

Figure 15 Reflction [24]

3.1.2. Diffraction

Diffraction occurs when the wireless signal hits a very large object, slows down and actually turns around the corner, when obstacles are impenetrable by the radio waves. Based on Huygen's principle, secondary waves are formed behind the obstructing body even though there is no line of sight.

Indoor environments contain many types of edges and openings, both orientated in the vertical and horizontal planes. Thus, the resultant diffracted signal will depend on the geometry of the edge, the spatial orientation, as well as on the impinging signal properties such as amplitude, phase and polarization. The result of diffraction on a wave striking an obstacle edge can be seen on Figure 16 where the wave front bends around and behind the obstacle edge.

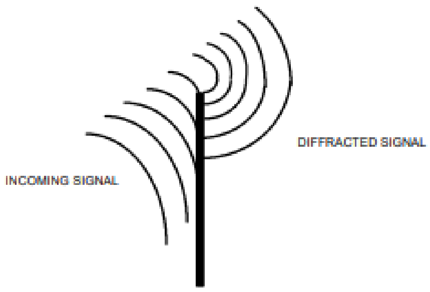

Figure 16 Diffraction [24]

3.1.3. Scattering

If there are many objects in the signal path, and the objects are small comparing to the signal wavelength, then the propagated wave front will break apart into many directions. The resultant signal will scatter in all directions adding to the constructive and destructive interference of the signal which is illustrated in Figure 17. Furthermore, construction materials such as conduit for electrical and plumbing service can add to the scattering effect.

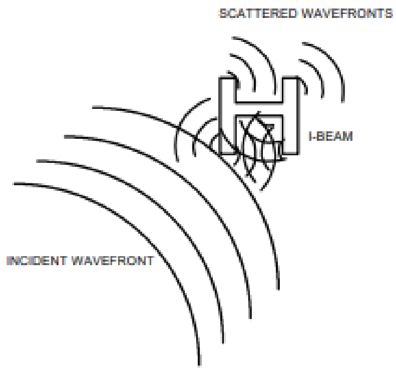

Figure 17 Scattering [24]

3.2. Spatial Diversity Antenna Systems

Spatial diversity antenna systems are used to overcome a phenomenon known as multipath distortion or multipath interference. A spatial diversity antenna system uses two or more identical antennas, located a small distance apart, to provide coverage to the same physical area.

3.2.1. Multipath Distortion

Multipath interference occurs when an RF signal has more than one path between a receiver and a transmitter, it is a combination of a primary signal and reflected, refracted or diffracted signal. This occurs in sites that have a large amount of metallic or other RF reflective surfaces. As the radio waves bounce, they can arrive at slightly different times and angles causing signal distortion and potential signal strength fading.

Just as light and sound, RF electromagnetic waves bounce off of objects. This means that there can be more than one path that the signal takes when going from a transmit (TX) to a receive (RX) antenna. These multiple signals combine in the receiver antenna to cause distortion of the signal which is illustrated in the Figure 18.

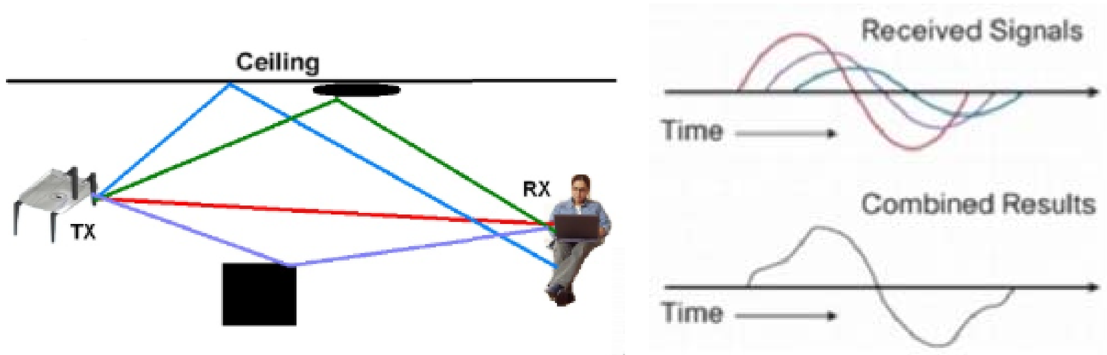

Figure 18 Multipath Distortion Arquitecture and Signal Result [11]

Multipath interference can cause the RF energy of an antenna to be very high, but the data would be unrecoverable. Changing the type and location of the antenna can eliminate multipath distortion.

Multipath often results in either an improvement ("constructive") or a downgrading ("destructive") type of interference. For constructive interference, the phase of the multiple signals are equals so the received signal has the same phase with a higher amplitude, resulting in an equal but stronger signal than the original one. In the case of destructive interference, the multiple signals have different phases and the received signal has a change in phase and amplitude. That implies that the addition of the different amplitudes at the different phases results in a signal that is not the one that was originally sent, making its decoding process very complex or even impossible. Both types of interferences are shown in Figure 19, with the resulting signal obtained from adding two signals from multipath distortion.

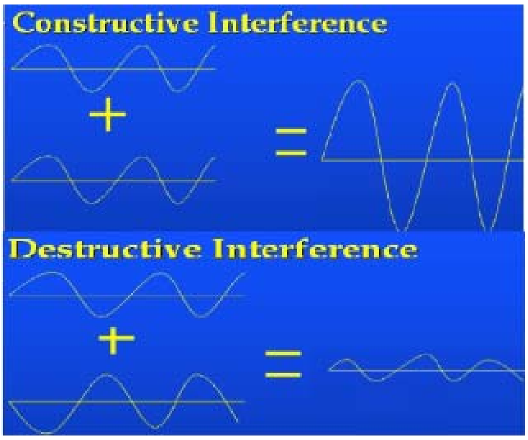

Figure 19 Constructive and Destructive Interference [11]

On the receiver side, because the distance travelled by the direct signal is shorter than the bounced signal, the time differential causes two or more signals to be received. These signals are overlapped and combined into a single one. The time between the first received signal and the last echoed signal is called the delay spread and it is the parameter used to signify multipath. Normally, multipath limits the data rate or lowers the performance. In the case of indoor 802.11n/MIMO systems, multipath is actually required for the system to operate at the highest data rates.

Indoor RF propagation is not the same as it is outdoor, due to the presence of solid obstructions, ceilings and floors that contribute to the attenuation and multipath signal losses. Therefore, multipath or delay spread is more a parameter used in the indoor environment. If the delay spread is higher, the interference increases and will cause lower throughput at a particular data rate.

3.2.1.1. Reduce Multipath Distortion

An antenna spatial diversity is a diversity scheme that uses two or more antennas to improve the quality and reliability of a wireless link. This scheme can be useful in scenarios of destructive interference and thus to reduce multipath distortion.

On the receiving side, the radio will switch between antennas listening for a valid packet. Once the beginning of the synchronization of a valid packet is heard, the radio will evaluate the synchronization signal of the same valid packet on all its antennas and evaluate. Finally, the radio will select the antenna with the best "hearing" of the synchronization signal and use only that antenna for the remaining portion of the packet.

On the transmitting side, the radio will select the same antenna it used for the last transmission it communicated to that given radio. If a packet fails, it will switch to the other antenna and retry the packet.

3.2.2. Fading

Interference and multipath cause the receive signal to fluctuate in time at a particular frequency. This variation of signal is called fading. Fading is also frequency selective, as attenuation varies with frequency. A channel can be classified as either a fast fading channel or slow fading channel. This depends on how rapidly the transmitted base band signal changes. A mobile receiver that travels through an indoor environment can receive rapid signal fluctuations caused by additions and cancellations of the direct signals at half wavelength intervals.

Interference increases the requirement of signal to noise ratio (SNR) for a particular data rate. The packet retry count goes up in an area where interference or multipath is very high. A change in the type and location of antenna can eliminate multipath interference. Antenna gain adds to the system gain and improves signal and interference to noise ratio (SINR) requirements.

Multipath introduces random variations in the received signal amplitude over a frequency bandwidth. Multipath effects also vary depending on the location of the antenna as well as the type of antenna used. The result of random signal distributions, as seen by the WLAN radio receiver, will be the “in and out” variation (fading) of the signal (variations as much as 40 dB can occur). Fading can be very rapid or slow. This depends on the moving source and the propagation effects manifested at the receiver antenna. Rapid variations over short distances are defined as small-scale fading. With respect to indoor testing, fading effects are caused by human activities and usually exhibit both slow and fast variations.

Although directional antennas help to focus the energy in a particular direction which can help to overcome fading and multipath, multipath itself reduces the focusing power of a directional antenna. The amount of multipath seen by a user at a long distance from the AP can be much more.

Directional antennas used for indoor typically have lower gain, and as a result, have a lower front-to-back and front-to-side lobe ratios. This results in less ability to reject or reduce the interference signals received from directions outside the primary lobe area.

3.3. Antennas

An antenna is a transducer (passive device) that transmit and/or receives electromagnetic waves (radio signal). It does not offer any added power to the signal. Instead, an antenna simply redirects the energy it receives from the transmitter. The redirection of this energy has the effect of providing more energy in one direction, and less energy in all other directions. Antennas are usually designed to operate at a specified frequency.

An antenna gives the wireless system three fundamental properties - gain, directivity, and polarization.

- Gain is a measure of increase in power. Wi-Fi antennas are typically rated in dBi. In the transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction. In a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power.

- Directivity measures the power density that the antenna radiates in the direction of its strongest emission, versus the power radiates by an ideal isotropic antenna (which emits uniformly in all directions) radiating the same total power.

- Polarization of an antenna refers to the orientation of the electric field of the radio wave and is determined by the physical structure of the antenna and by its orientation.

The elevation angle is the “up” and “down” angle (vertical) from a reference plane, generally the horizonal and the Azimuth angle is the “left” and “right” angle (horizontal). There are multiple combination angles possible.

The phase is a complex function of the antenna and surroundings. Phase can be constructive or destructive as seen before, by allowing the antenna to work well in performance or to be destructive where it could severely affect the antennas performance.

3.3.1. Omnidirectional Antennas

Omnidirectional antennas provide a 360° donut shaped/horizontal radiation pattern to provide the widest possible signal coverage for outdoor and indoor wireless applications. It sends a signal out equally in all directions around it.

These are used when coverage is required in all direction (horizontally) from the antenna with varying degrees of vertical coverage. An omnidirectional antenna is usually a vertical polarized antenna. The radiation pattern of omnidirectional antennas is shown in Figure 20 where the elevation angle (vertical) and Azimuth angle (horizontal) are illustrated.

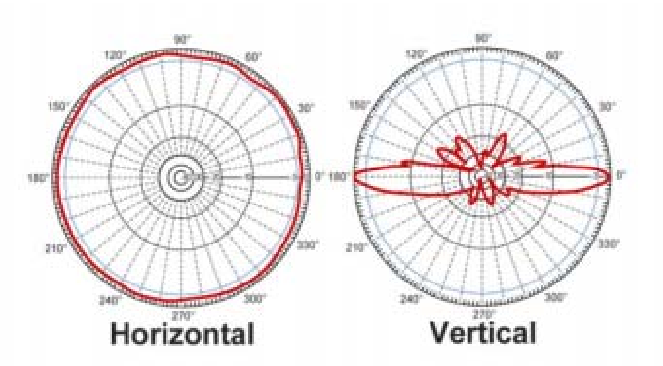

Figure 20 Typical Omnidirectional Antenna Ratiation Pattern [25]

Figure 20 illustrates the radiation pattern of HG2415U-PRO antenna, which is an omnidirectional antenna operating at 2,4 GHz. This antenna is shown in the next figure, Figure 21.

Figure 21 HG2415U-PRO Omnidirectional Antenna [26]

The all-direction strength of these antennas comes with a drawback of transmitting a weaker signal. Since the signal is going in all directions, it spreads out and gets weaker with the distance faster. If nodes or clients are far away, they may not connect well. This type of antennas can deliver very long communications distances but has another drawback which is poor coverage below the antenna. This poor coverage under the antenna is shown in Figure 222.

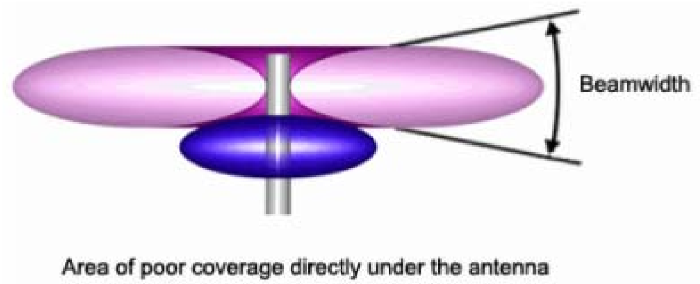

Figure 22 Omnidirectional Antenna with No Coverage Below the Antenna [27]

The omnidirectional antenna is usually a vertically polarized antenna, so you cannot have advantages of using cross polarization to fight interference [27].

A low gain antenna provides a perfect coverage for an indoor environment. It covers more area near the AP or a wireless device in order to increase the probability of receiving the signal in a multipath environment.

Typical applications for omnidirectional antennas include, in the indoor case, office spaces, retail stores, warehouses, small office or home networks where there is no requirement for directional antennas and the unit will be ceiling mounted.

3.3.2. Directional Antennas

Directional antennas send out a signal in a more focused way than the omnidirectional antennas. It focuses the wireless signal in a specific direction resulting in a limited coverage area, although it does not get additional RF power. As the gain of a directional antenna increases, the angle of radiation usually decreases, providing a greater coverage distance, but with a reduced coverage angle. This redirection of energy in the case of directional antennas is illustrated in the Figure 23 where it can be seen that it will have a narrow azimuth beamwidth and a narrow elevation beamwidth.

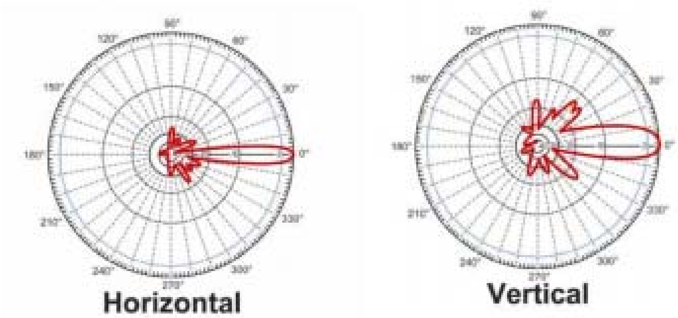

Figure 23 Typical Directional Antenna Radiation Pattern [25]

Figure 23 illustrates the radiation pattern of HG2424EG-NF antenna, which is directional antenna operating at 2,4 GHz. This antenna is shown in Figure 24.

Figure 24 HG2424EG-NF Directional Antenna [28]

Using directional antennas has the benefit of increasing the distance of a signal that will travel in one direction, while reducing it in all other directions. The node has a very powerful signal in a single direction. A drawback of these kind of antennas is that they require more planning, since it defines and limits the areas where wireless signals go, it will be needed to think about how those signals cover the localization.

With the directional antennas, the RF energy can be directed in a particular direction to farther distances. Therefore, it can cover long ranges, but the effective beamwidth decreases. This type of antenna is helpful in near LOS (Line of Sight) coverage, such as covering hallways, long corridor, isle structures with spaces in between, etc. However, as the angular coverage is less, you cannot cover large areas. This is a disadvantage for general indoor coverage because where it would be likely to cover a wider angular area around the AP.

3.3.2.1. Concept of Downtilt

One aspect of using directional antennas is the concept of mechanical downtilt. Downtilt involves adjusting the antenna’s angle down to change the coverage pattern that is created.

The coverage pattern can be adjusted by changing the height and/or the mechanical downtilt angle parameters. Elevation plane has nulls due to high gain, but the antennas were designed with “Null-Fill” meaning that the overall antenna gain is scaled back to have less nulls or low signal spots on the ground (Figure 25) [11].

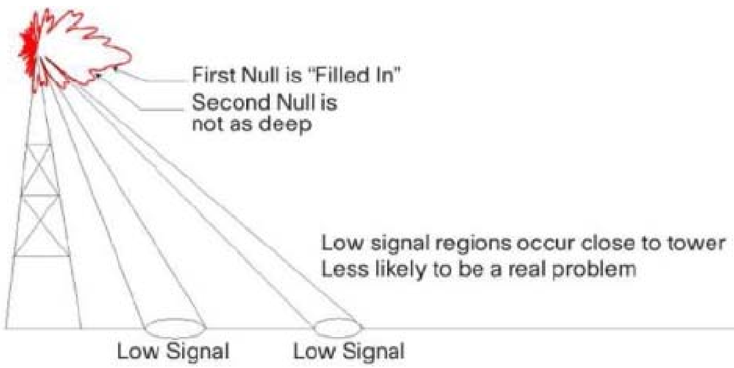

Figure 25 Reduced Coverage Gaps from a Sector Antenna with “Null Fill" [11]

Adjusting the directional antenna can be done by changing the height of the antenna and/or the mechanical downtilt angle and its effect is illustrated in Figure 26.

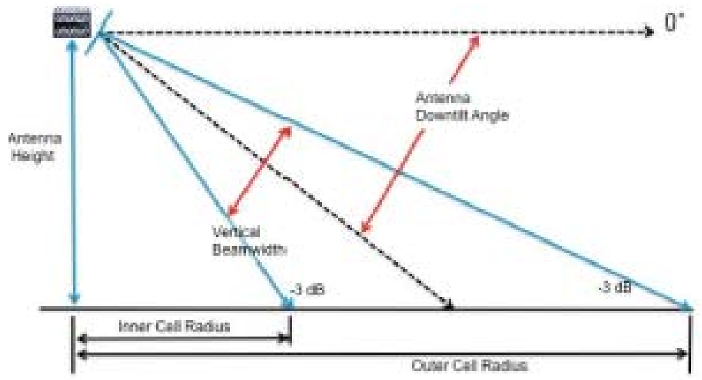

Figure 26 Adjusting Directional Antenna Using Downtilt [29]

From Figure 26, it can be seen that by changing the parameters of the height and downtilt angle, the two radii (inner and outer radii) change their size. Starting from the point just below the AP, the inner radii defines the distance at which the Wi-Fi coverage begins and the outer radii defines the distance at which the Wi-Fi coverage ends. The total coverage distance will be the difference between the outer and the inner radii.

The value of those radii can be calculated by applying the following formula (Formula 1) [29]:

$$\text{Inner Radii} = {}^{h}\!/_{\tan(A+\frac{BW}{2})}; \qquad \text{Outer Radii} = {}^{h}\!/_{\tan(A-\frac{BW}{2})}$$

Formula 1 Inner and Outer Radii of Directional Antenna

With 'h' being the height of the antenna, 'A' the mechanical downtilt angle and 'BW' the 3-dB elevation plane beamwidth of the antenna.

By placing the AP at a higher height, the inner and the outer radii will be bigger (farther away from the AP and bigger covered area) and by placing it at a lower height, those radii will be smaller (closer to the AP a smaller covered area). So, the coverage distance of the antenna will depend on the height of the antenna (higher would make it bigger and lower would make it smaller).

By increasing the mechanical downtilt angle, the inner radii and the outer radii will be smaller (closer to the AP and smaller coverage distance) and by decreasing the mechanical downtilt, the inner rand outer radii will be bigger (farther away from the AP and larger coverage distance).

3.3.3. Conclusion

While directional antennas can be great value for certain indoor application, the vast majority of indoor installations utilize omnidirectional dipole antennas for the reasons cited above. The selections of an antenna should be strictly determined by a proper and correct site survey.

In Table 6, the different antennas are described with their recommended deployments.

Antenna Type	Description	Deployment
Omnidirectional	Creates a 360-degree coverage pattern. Circular pattern covers wide areas. Ceiling mounted.	Open offices areas, conference rooms, warehouse.
Directional	Focuses the radio signal to direct the energy in certain directions. These antennas are typically mounted on a wall and provide coverage in a limited-angle pattern.	Hallways or office corridors.

Table 6 Resume Antenna Type: Omnidirectional, Directional and Dipole

3.3.4. Placement

AP antennas need to be placed away from reflective surfaces for best performance, since the reflective surfaces will only decrease the signal strength. Moreover, it is imperative to avoid metal support beams, lighting and other obstructions, since metal objects causes increased multipath and directionality.

When possible or practical to do so, always mount the AP (or remote antennas) as close to the actual users as you reasonably can. Avoid the temptation to hide the AP in crawl spaces or areas that compromise the ability to radiate well.

Omnidirectional antennas must be mounted on ceilings whereas dipole and directional antennas can be either mounted on ceiling and on walls.

4. Implementation of An Improved Wi-Fi Network

In order to obtain the best results for the implementation of a Wi-Fi network, a predictive study of the network is needed. In a predictive site survey, it is important to make first a complete design of the network, including a network plan. The site survey made for this project was accompanied with the help of the Ekahau HeatMapper software [30].

For the expectations to be as real as possible, it is important to consider all the factors that can affect the wireless signals.

On one hand, the theoretical study has to be related to the propagation of the wireless signal. Because of the fading, there is a decrease (a fall) in the power received due to variations in the conditions of propagation in space and time. The design must ensure that, inside the AP's radii, the power received is strong enough to be able to extract the data.

On another hand, the predictive design must also consider the capacity of the network. The capacity, in the context of network, is the measurement of the maximum amount of data that may be transferred between network locations over a link or network path. This is an important factor since nowadays many devices are connected at the same time, with a high demand of connectivity and many crowded open spaces.

4.1. Current network

This End-of-Grade project is centered in the implementation of the Wi-Fi network in the Reyers site of the RTBF that is located in Brussels. A picture of the site in question is shown in Figure 27, where the RTBF is limited by the yellow form. In order to implement a Wi-Fi network in the building, first the actual Wi-Fi network has to be analyzed to understand the different problematics of the site and to study the feasibility of improving the capacity, coverage and performance of the Wi-Fi network.

Figure 27 Reyers Site of the RTBF [31]

The Reyers building provides all the studios needed for the radio and the television shows. It is a building that homes more than a thousand people every day.
To understand better the design implemented, a review of the characteristics and the key spaces of the building is done below.

The actual implemented Wi-Fi network is a best-effort network. Due to the fast expansion of connected devices, the network did not follow and create many holes of coverage and a lack of coverage in many parts of the building that will be illustrated later.

4.1.1. Characteristics of the building

The current network count with 104 installed APs and 58 APs are stocked and ready to use. The RTBF Reyers site is two buildings jointed by a main corridor.

First, the smaller building has 5 floors in total, each of one has 8,9 km².

On the ground floor, there is the NOC (Network Operation Center) and the ICT (Information and Communication Technologies) room. The remaining space of the floor is used for some offices and stocking.

The first floor is dedicated mainly to the television studios. There are three studios in use with their corresponding accommodations. The rest of the floor are offices.

On the second, third and fourth floors, there is the cafeteria and offices.

Secondly, the bigger building can be divided on two parts:

- From the eleventh to the fifth floor, each floor has 1,6 km². On those floors, some meeting rooms, offices and open spaces can be found.
- From the fourth to the ground floor, each floor has 6,25 km².

An open patio goes from the third to the fourth floor, with spaces for interviews and to work for the journalists. On those two floors, there also is the main radio studios, another cafeteria and two radio studio that also go on television.

On the third floor, there is the newsroom which is mainly an open space with around 60 people working all day long.

The second floor is composed of meeting room, offices and open spaces.

One half of the first floor is rented to a private university and on the other half there are offices and some stocking spaces.

Finally, the ground floor is mainly a parking, with some stocking and office rooms.

The offices contain standard steel office furniture with Formica tops. Most offices are occupied by more than one person (between 2 and 5) accompanied by a typical assortment of books, computer equipment, and limited number of lamps, and fans. Some of the walls hold pictures, dry erase and cork boards.

4.1.2. Key spaces

The key spaces of the building are the location within the Reyers site that are the most important, concerning the Wi-Fi coverage, for the enterprise. These are the spaces dedicated to the proper providing of the services, where the live shows are made, where the journalists receive their guests for interviews and where worker must be able to connect to the Internet at any time in a mobile way.

4.1.2.1. Studios

Being a Radio and Television distributor, the RTBF has 13 radio studios and 3 television studios.

Each radio station will need its own AP because the soundproofing materials do not let the Wi-Fi signals pass through.

For the television studios, it is complicated to implement a Wi-Fi coverage because of the installations of the cameras, micro and lightings. Moreover, many wireless micro and cameras work at the frequency of 2.4 GHz which is the frequency used also in Wi-Fi. It is important to be careful to disable the 2.4 GHz band on the APs to avoid interference.

4.1.2.2. Patio

The patio is placed over two floors. It is a place separated by decorations into "lounges" for the journalist interviews. There is a lot of decoration (plants, glass) at high height and a stair in the middle of the patio (between the third and the fourth floors) that attenuate the Wi-Fi signals at a strength that depends on the location of the end-device to the AP.

Also, an issue with the patio is that it is opened and the roof is made of glass and no hardware can be mounted at that height and on that kind of material. Because of that, the Wi-Fi network should cover the place from the sides.

4.1.2.3. Newsroom

The newsroom is an open space with over 60 journalists. There are mounting cellule separated from the open space by glass walls. There are many televisions around the room.

The attenuation in the newsroom is really hard to predict since it depends on the movement and number of people in the room and on the use of Bluetooth technologies (many interferences where found). Also, the fact that the televisions are turned on or turned off make a change in the attenuation of the Wi-Fi signals.

In terms of capacity, there must be enough AP to allow the use of streaming, downloading and voice application for all the devices.

4.1.3. Lack of coverage

During the site survey performed, an important lack of coverage was found out due to the low number and the localization of the installed APs.

To illustrate the absence of installed APs, a simulation of the Wi-Fi coverage on two different with the following results: on the Figure 28 and Figure 29, the Wi-Fi coverage of the second and eleventh floors at 2.4 GHz; and on the Figure 30 and Figure 31, the second and eleventh floors at 5 GHz.

To make these simulations, the Cisco Prime Map infrastructure was used [32]. This function allows the user to enter a calibrated map and to add obstacles like thick and thin walls. Placing the APs models installed and the obstacles on the map of the second and eleventh floors, a simulation of the Wi-Fi coverage at 2.4 GHz and 5 GHz is calculated.

4.1.3.1. 2.4 GHz band

Second Floor

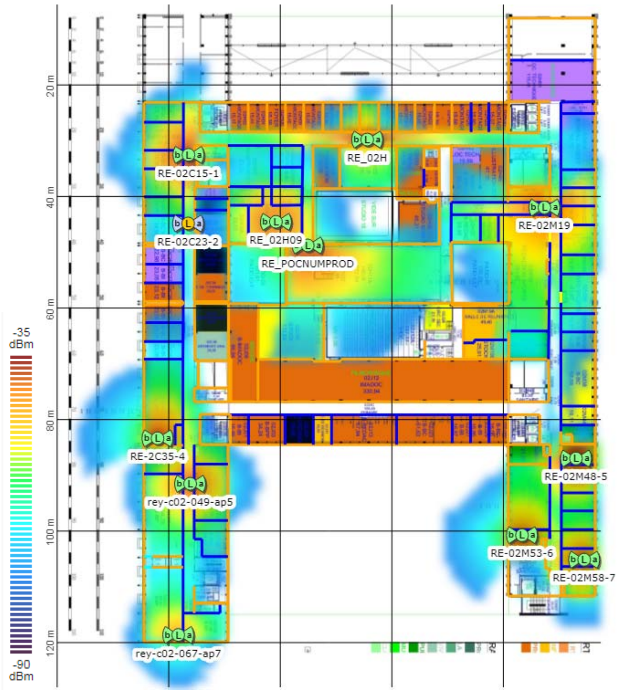

Figure 28 Cisco Prime Maps Representation of the Second Floor Coverage at 2.4 GHz

Eleventh Floor

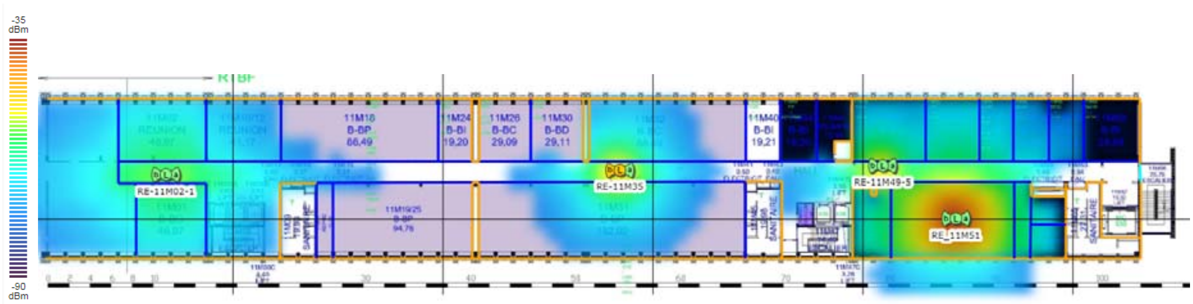

Figure 29 Cisco Prime Maps Representation of the Eleventh Floor Coverage at 2.4 GHz

It can be easily seen that there are many coverage holes in the second and eleventh floors. Moreover, it is recommended that on the cell edge, the RSSI should not go under the -65 dBm which is obviously not respected. Also, the overlapping of the cell's edges is inexistent.

4.1.3.2. 5 GHz band

Second Floor

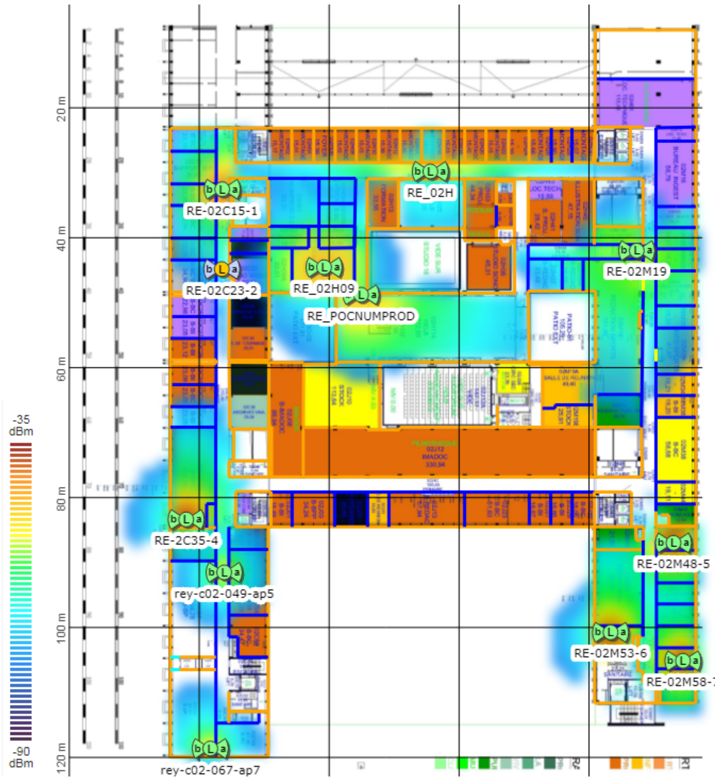

Figure 30 Cisco Prime Maps Representation of the Second Floor Coverage at 5 GHz

Eleventh Floor

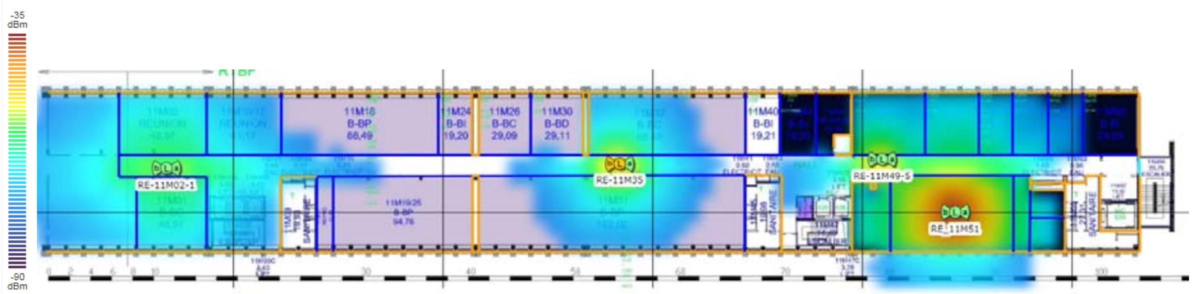

Figure 31 Cisco Prime Maps Representation of the Eleventh Floor Coverage at 5 GHz

As expected, the covered areas of the APs are smaller at 5 GHz than at 2.4 GHz. Also, the attenuation due to the obstacles has more impact on the wireless signal at 5 GHz than at 2.4 GHz.

It is clear that this Wi-Fi network was not properly designed: the network was not designed for a 5 GHz coverage and the APs placements do not follow a pattern what causes holes in the coverage. These APs were placed according to the requests of the workers and not implemented as a full covered building.

4.2. Problematics encountered

The RTBF Reyers site's Wi-Fi implementation can be delicate for diverse reasons. These reasons are: the building itself, the testing issue due to broadcasting, the misplacement of the APs and the Rogues APs. These points are explained below.

4.2.1. Building

First of all, the site was built in the 60’s. This imply that the materials used were often thicker and that the attenuation due to the materials is higher.

Also, through the years, many changes have been made in the building and not all of those changes are reflected in the plans. For example, the material and the thickness of the walls are not registered and most of the open spaces are not updated on the plans.

Because of these reasons, it was difficult to be able to define exactly the attenuation of each obstacle. The measurements had to be done manually for every kind of obstacle, measuring the RSSI level on each side of the obstacle.

Moreover, there was no existing plan of the actual Wi-Fi network with the exact localizations of the APs. A full site survey, including the localization of each APs had to be done in order to implement a new Wi-Fi network based on the existing one.

4.2.2. Testing

In order to be precise in the attenuation’s study, measurements had to be done for every obstacles encounter, including in the key spaces.

Being a national television and radio broadcaster, the RTBF have many studios. For the television studios, it was delicate to test the attenuation of the place since it is often used for direct shows like the news and cannot be accessed. Also, if testing an installation made, any interference created with the existing devices is irreversible.

Television studio’s attenuation is also changing depending on the show. The height of the lightning, the decorations and the devices (microphone, cameras) are movable which improve the difficulties of defining the exact attenuation in those locations.

Also, a similar problem was encountered in the newsroom, where many journalists works at any time of the day and every day. Having so many persons moving around makes the measurement of the attenuation hard to define.

Those measurements had to be done out of the business hours to avoid disturbing the workers and to be able to define the attenuation best.

4.2.3. Access Points Placement

During the site survey, many APs had peculiar placements. Some review on the wrong and good placement of AP is going to be done.

First of all, it is imperative to place an omnidirectional antenna on the ceiling and not on the walls. Only directional and dipole antennas can be place on both the ceiling and the wall. A misplacement of this kind is shown in the Figure 32, which is a picture that has been taken inside the building.

Figure 32 Wrong Placement of an Omnidirectional Antenna

The problem with that misplacement is that the donut shaped horizontal radiation pattern of the omnidirectional antenna is now vertical what imply a strong radiation on a vertical plane but a weak radiation on the horizontal plane; in other words, the antenna will radiate through the floors and interfere with the APs placed on the upper and lower floors and will not cover the expected area horizontally.

Also, the placement of an AP cannot be too close from metal obstacles since it is one of the most attenuating signal materials. APs have been founded under the false metallic ceiling, attenuating over 10 dB the signal. This kind of error in placement is shown in Figure 33 where there is a misplacement in the orientation and position of the omnidirectional AP, which is a picture that has been taken inside the building.

.

Figure 33 Wrong Placement of an Access Point

Finally, in the case of directional antenna placement, it is important to orient the direction of the external antennas properly. To properly orient the antennas, their radiation diagram must be analyzed. A misorientation of external antennas is shown in ***¡Error! No se encuentra el origen de la referencia.***, which is a picture that has been taken inside the building. This kind of misplacement can disturb the expected coverage pattern of the APs.

Figure 34 Wrong Placement of Antenna on a Directional Antenna

4.2.4. Rogue Access Points

A rogue access point is a wireless AP that has been installed on the existing secured network without explicit authorization from a local network administrator. During the site survey, many rogue APs where found, mainly due to the lack of secured Wi-Fi network coverage. This problem is represented in the ***¡Error! No se encuentra el origen de la referencia.***, where the rogue APs are framed in blue and the secured network APs are frame in black. Figure 35 is the result of a part of the site survey made using Ekahau HeatMapper program.

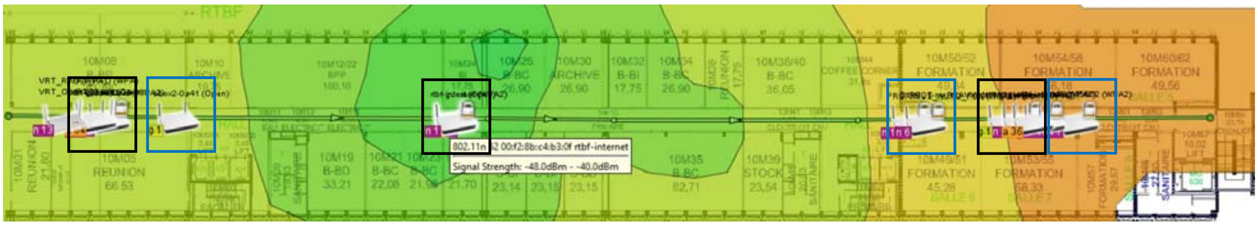

Figure 35 Rogue Access Points in a Secured Network

All the secured network APs are linked to a controller. The controller implements different functionalities in order to avoid interference of all types on the network, for example a dynamic channel selection, a dynamic transmission power selection, and so on.

There are two problems implied in the installation of rogues APs in the building:

- By installing rogue APs near the secured network APs, it creates interference between the different network. The controller of the secured network is not informed of the presence of rogue APs, so it cannot consider their parameters. Thus, the interference caused by the rogue APs cannot be held by the controller because of a lack of information.
- Moreover, the rogue APs are not secured and not connected to the central controller. It makes it impossible to manage the traffic that passes through these APs and it create a flaw in the complete security of the network.

4.3. Hardware Characteristics

The hardware used for the implementation of a Wi-Fi network is, in this case, different APs from Cisco and the end-points with integrated Wi-Fi modules. The different characteristics used for the calculations of the Wi-Fi coverage will be explained as well as some antennas concepts (MIMO characteristics and beamforming concept).

4.3.1. Access Points

The company is using five different series of Cisco's AP. Those models used are shown in Table 7 with their corresponding model's name, operating frequency band and the 802.11 standards supported. Table 7 was created based on the datasheets of the different Cisco AP products [33].

Series	Model	Operating Band	Standard	Wave
Series 1260	AIR-LAP1262N-E-K9	Dual-Band	a/g/n	-
Series 2600	AIR-CAP2602E-E-K9	Dual-Band	a/g/n	-
Series 2700	AIR-CAP2702E-E-K9	Dual-Band	a/g/n/ac	Wave 1
Series 2700	AIR-CAP2702I-E-K9	Dual-Band	a/g/n/ac	Wave 1
Series 2800	AIR-AP2802E-E-K9	Dual-Band	a/g/n/ac	Wave 2
Series 2800	AIR-AP2802I-E-K9	Dual-Band	a/g/n/ac	Wave 2
Series 3600	AIR-CAP3602I-EK9	Dual-Band	a/g/n	-

Table 7 Operating Band and Standard of the Available Access Points

NOTE: The 'E' or 'I' in the model's names means the AP has external or integrated antennas respectively.

NOTE: The company has updated the version of its controller, passing from the version 6 to the version 8. This update of the controller has made the use of the APs Serie 1260 obsolete since it does not support that series anymore. For that reason, the Series 1260 is not considered in the new implementation of the Wi-Fi network.

All the Wi-Fi standards of the different APs used in the company are retro compatible with each other. As long as both devices (the AP and the endpoint) are on the same frequency band, the device that supports the latest (or higher performance) standard will fit the older (or lower performing) standard. Since all the APs used are dual-band, it will be a misspend to use other standards that the ones with higher performance (802.11n and 802.11ac).

So, for the 2600, 2700, and 3600 Series, the 802.11n standard will be used and for the 2800 Series, the 802.11ac standard will be the one chosen to be in use. By doing that, the best standard available for the device is guaranteed at any time. If any end-device would not integrate those standard, the standard in use will be the latest one of the end-device.

For each model used in the implementation of the Wi-Fi network, Table 8 gather the minimum and maximum RSSI for the different modulations and the gain of the antennas used (integrated and external antennas). Again, Table 8 was created based on the datasheets of the different Cisco AP products [33].

Series	Minimum RSSI	Maximum RSSI	Antenna Type	Antenna Gain
Series 2600	-89 dBm	-69 dBm	External	4 dBi
Series 2700	-90 dBm	-66 dBm	External	4 dBi
Series 2700	-90 dBm	-66 dBm	Internal	4 dBi
Series 2800	-89 dBm	-67 dBm	External	4 dBi
Series 2800	-89 dBm	-67 dBm	Internal	4, 5 or 6 dBi *
Series 3600	-88 dBm	-68 dBm	Internal	4 dBi

Table 8 RSSI and Antenna Gain for the Available Access Points

(*) Depending on the operating band, the gain of the antenna's changes. Operating on dual-band, at 2.4 GHz the gain of the antenna is of 4 dBi and at 5 GHz it is 6 dBi. Using the APs at 5 GHz only with the dedicated radio, the gain of the antenna is 5 dBi.

The external antennas are directional antennas and the integrated antennas are omnidirectional antennas.

From the Table 8, the most restrictive RSSI is the one of the Series 2700 with -66 dBm. It is an important data to consider when calculating the coverage of the APs since it is the most restrictive value which will define the limitation of the system.

The maximum transmit power of the APs is 23 dBm [49] but legally, in Europe, the maximum transmit power is limited to 20 dBm [33].

For each Series of APs, Table 9 shows the technologies implemented with their corresponding spatial streams. Again, Table 9 was created based on the datasheets of the different Cisco AP products [33].

Series	Beamforming	Spatial Streams	MIMO
Series 2600	Yes	3 SS	MIMO 3x4
Series 2700	Yes	3 SS	MIMO 3x4
Series 2700	Yes	3 SS	MIMO 3x4
Series 2800	Yes	3 SS	MIMO 4x4
Series 2800	Yes	3 SS	MIMO 4x4
Series 3600	Yes	3 SS	MIMO 4x4

Table 9 Antennas Technologies of the Available Access Points

It can be seen that all the models of APs used in the implementation of the Wi-Fi network integrate the beamforming and MIMO technologies with three spatial streams (3 SS). Those technologies will be explained later in this document.

4.3.2. End-Point Wi-Fi Modules

To ensure the client device's integration to the network, different Wi-Fi modules have been considered for the theorical study of the implementation of a Wi-Fi network.

The two modules considered are:

- Cypress CYW4339 module
- Skylab SKW78 module

Those two Wi-Fi modules are both operating in dual-band and compliant to 802.11 a/b/g/n/ac. Moreover, they both support 20 MHz, 40 MHz and 80 MHz bandwidth.

The Skylab module integrates MIMO antennas technology. Operating in dual-band, the four transmitting and four receiving antennas can be used simultaneously. Using dedicated radios, only two transmitting and two receiving antennas can be used for each band.

The Cypress module proposes additional external antennas to be able to provide the MIMO technology (only one transmitting and receiving antenna is integrated to the module).

For the two Wi-Fi module considered, Table 10 gather the minimum and maximum RSSI for the different modulations and their maximum transmit power. Table 10 was created based on the datasheets of the Wi-Fi module, the CYW4339 [34] and the SKW78 [35].

Wi-Fi Module	Minimum RSSI	Maximum Transmit Power
CYW4339	-66 dBm	17 dBm
SKW78	-63 dBm	13 dBm

Table 10 Minimum RSSI and Maximum Transmit Power of the CYW4339 and SKW78 Wi-Fi Modules

From the characteristics of the APs and the Wi-Fi module, the theorical calculus can be based on those values.

An antenna gain of 3 dBi is considered for the end-devices, since it is the medium value for smartphones, laptops and tablets (end-devices).

4.3.3. Multiple Antennas Structures

Multiple antennas structures can be classified into single-input single-output (SISO), single-input multiple-outputs (SIMO), multiple-inputs single-output (MISO) and multiple-inputs multiple-outputs (MIMO) systems.

4.3.3.1. SISO

With the SISO technology, the more devices are connected to the wireless network, the lower will be Wi-Fi signal. This is because in a SISO system, the AP sends the Wi-Fi signal to one device at a time. Each device waits for its turn to send and receive data over the Internet, and as soon as another device connects to the Wi-Fi network, the queue becomes longer.

This is effectively a standard radio channel: the transmitter operates with one antenna as does the receiver. There is no diversity and no additional processing required.

The advantage of a SISO system is its simplicity. SISO requires no processing in terms of the various forms of diversity that may be used. However, the SISO channel is limited in its performance. Interference and fading will impact the system more than a MIMO system using some form of diversity, and the channel bandwidth is limited by Shannon's law (the throughput being dependent upon the channel bandwidth and the signal to noise ratio) [36].

Then SISO technology is shown in ***¡Error! No se encuentra el origen de la referencia.***, where there is one transmitting antenna and one receiving antenna.

Figure 36 Single-Input Single-Output [37]

4.3.3.2. SIMO

The SIMO version occurs when the transmitter has a single antenna and the receiver has multiple antennas (**¡Error! No se encuentra el origen de la referencia.**7). This is also known as receive spatial diversity. It is often used to enable a receiver system that receives signals from a number of independent sources to combat the effects of fading. It has been used for many years with short wave listening/receiving stations to combat the effects of ionospheric fading and interference.

Figure 37 Single-Input Multiple-Output [37]

SIMO has the advantage that it is relatively easy to implement although it does have some disadvantages which one of them is that processing is required at the receiver. The use of SIMO may be quite acceptable in many applications, but where the receiver is located in a mobile device such as a cellphone handset, the levels of processing may be limited by size, cost and battery drain.

There are two forms in which SIMO that can be used:

- *Switched diversity SIMO:* This form of SIMO looks for the strongest signal and switches to the antenna that provides it.
- *Maximum ratio combining SIMO:* This form of SIMO takes both signals and sums them to give a constructive combination of them. In this way, the signals from both antennas contribute to the overall signal.

4.3.3.3. MISO

MISO is also termed transmit diversity. In this case, the same data is transmitted redundantly from the two transmitter antennas (**¡Error! No se encuentra el origen de la referencia.**). The receiver is then able to receive the optimum signal which can be used to extract the required data.

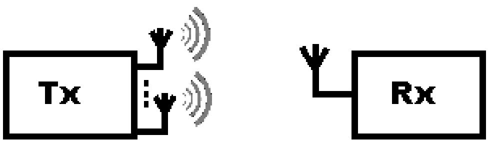

Figure 38 Multiple-Input Single-Output [37]

The advantage of using MISO is that the multiple antennas and the redundancy coding/processing is moved from the receiver to the transmitter. In instances such as cellphone, this can be a significant advantage in terms of space for the antennas and reducing the level of processing required in the receiver for the redundancy coding. This has a positive impact on size, cost and battery life as the lower level of processing requires less battery consumption.

4.3.3.4. MIMO

The MIMO is when there is more than one antenna at either end of the radio link (Figure 39). MIMO can be used to provide improvements in both channel robustness as well as channel throughput.

In order to be able to benefit from MIMO fully it is necessary to be able to utilize coding on the channels to separate the data from the different paths. This requires processing but provides additional channel robustness and data throughput capacity.

Figure 39 Multiple-Input Multiple-Output [37]

As we know, capacity is a performance for digital communication systems. It is the maximal transmission rate for which a reliable communication can be achieved. If the transmission rate gets larger than the capacity, the system breaks down and the receiver makes decoding errors with a non-negligible probability. Capacity is the primary tool to characterize the performance of MIMO systems and it also serves in practical system as a guide to properly design the transmitted signals as well as the processing of the received signal.

MIMO technologies use transmit and/or receive antenna arrays to improve signal-to-noise ratio (SNR) quality and/or transmission rate. It also makes possible the ability to reduce the level of emission of the radio signals to reduce the surrounding electromagnetic pollution, but also to extend the battery life in the case of a cellphone.

Three main categories of MIMO can be considered:

- *MIMO spatial diversity:* the same message is simultaneously transmitted on different antennas on transmission. The signals received on each of the reception antennas are then re-phased and summed coherently. A simplified version uses the signal of only one of the antennas, the one that receives the best signal at a given moment (polarized antennas). This makes it possible to increase the Signal-to-Noise ratio (thanks to the diversity gain) of the transmission. For this technique to be effective, the MIMO subchannels must be decorrelated (independent) from each other.
- *MIMO spatial multiplexing:* each message is split into sub-messages. The different sub-messages are simultaneously transmitted on each of the transmitting antennas. The signals received on the receiving antennas are reassembled to reconstruct the original message. As with MIMO spatial diversity, the propagation subchannels must be decorrelated. MIMO multiplexing makes it possible to increase the transmission rates (thanks to the multiplexing gain). MIMO diversity and multiplexing techniques can be applied together. For example, for a 5 x 5 MIMO system (i.e. 5 transmit antennas and 5 receive antennas), a 2 x 2 MIMO subsystem can be configured to multiplex and a MIMO subsystem 3 x 3 to make MIMO spatial diversity.
- *MIMO - Beamforming:* the MIMO antenna network is used to orient and control the radio wave beam (beam amplitude and phase). Constructive/destructive lobes can be created and transmission between the transmitter and the target optimized. Beamforming techniques both extend radio coverage (from a base station or AP, for example) and limit user interference with surrounding electromagnetic pollution (targeting the intended receiver).

4.3.3.5. Comparison of Capacity for SISO, MISO, SIMO and MIMO

The comparison of the capacity of the different multiple antennas systems will be done, supported by graphs that represents the capacity depending on the SNR level and on the number of antennas involved

(Figure 40). Considering 'N' as the number of transmitter antennas and 'M' as the number of receiver antennas:

- In the SISO case (N=1, M=1), capacity range from 1 to 16 bps/Hz. It remains low and increases slowly with the SNR, which illustrates the limitations of SISO transmissions.
- With MIMO the example of four antennas (N=4, M=4), capacity ranges from 3 to 48 bps/Hz (3 times larger than with the SISO system). It increases rapidly with the SNR, which illustrates the performance of a MIMO communication.

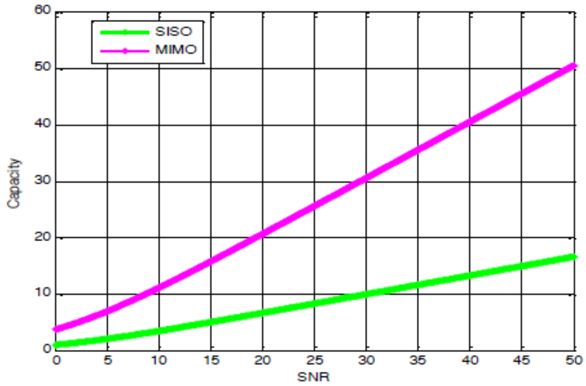

Figure 40 SISO and MIMO Systems Capacity Depending on the SNR [38]

The ***¡Error! No se encuentra el origen de la referencia.*** illustrates the increase of capacity accordingly to the number of antennas for all systems with a fixed SNR value.

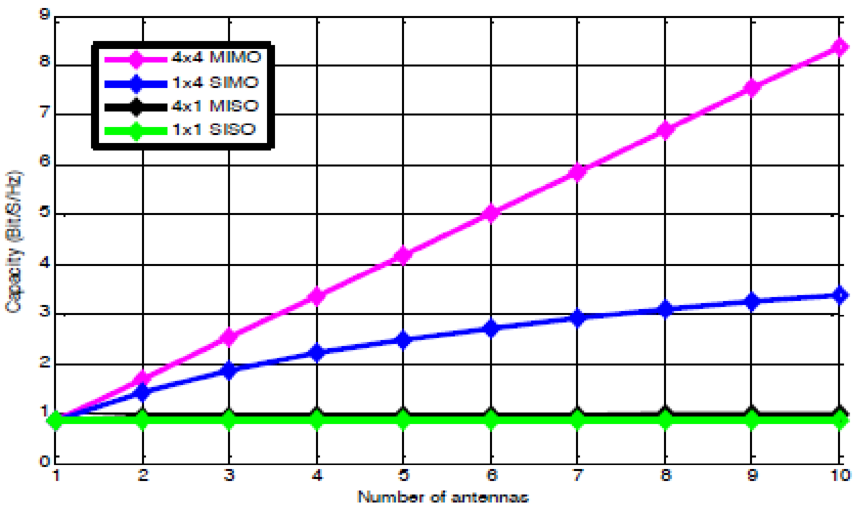

Figure 41 SISO, SIMO, MISO and MIMO Systems with a Fixed SNR for Four Antennas [38]

By increasing the number of transmitting and receiving antennas with a fixed SNR of 15 dB, we can observe that MIMO capacity grows linearly with respect to the number of antennas and it is approximately M times larger than SISO capacity.

For MISO, the performance gain is negligible when the number of transmit antennas increases.

The SIMO system is more efficient than SISO and MISO systems; it gets high capacity with increasing number of antennas which illustrates the limitations of SISO and SIMO transmissions.

For a SIMO system, the capacity follows a logarithmic trend when we increment the number of antennas at the reception while the MIMO system increases linearly when we increase the number of transmit and receive antennas. The advantage (in term of capacity) of MIMO systems is mainly due to the exploitation of multipath. First, they allow the receiver to distinguish the different transmitting antennas, and therefore to simultaneously transmit multiple symbols. Then, each path is a replica of the transmitted signal, and therefore carries useful information. Each path is equivalent to the direct signal emitted by a virtual antenna, which virtually increases the number of transmit antennas. The price to pay for this increase in capacity is first material, with the proliferation of antennas and their associated electronics, but also software with much more complex receivers and asking for more calculation's power and therefore increase consumption.

Finally, degradation of the correlation coefficient between the antennas can result in reduced capacity. By increasing the number of antennas for many MIMO systems, capacity increases with. This is shown in Figure 42.

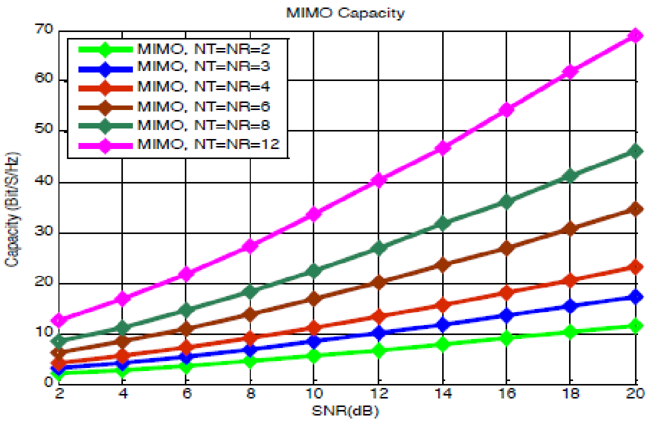

Figure 42 MIMO Systems Capacity Depending on the Number of Antennas and on the SNR [38]

As it can be seen in Figure 42, MIMO capacity increases much more rapidly with higher SNR.

There are two variants of MIMO according to the number of users simultaneously receiving data on the same carriers:

- The most common, SU-MIMO (Single User MIMO), makes it possible to send data via the different antennas to a single user at a given moment; it requires to have several antennas in each receiver. This mode achieves a higher peak unit rate. It was used before the 802.11n standard.
- The MU-MIMO (Multi User MIMO) is used to share the radio speed and transmit data streams to more than one user, for example with 4 transmit antennas and 2 antennas in each receiver. It uses the "spatial multiplexing" mode and makes it possible to increase the spectral efficiency of the radio cell (the overall rate) without imposing a high number of antennas in each terminal. This is used from the 802.11n standard.

MIMO is based on using multiple transmit and receive antennas to improve the system performance. This technology requires a separated radio-frequency chain and an analog to digital converter for each MIMO antenna which increases the implementation costs compared to the systems without MIMO technology.

4.3.3.6. MU-MIMO

The MU-MIMO technology gives the ability to connect an AP to multiple devices at the same time using multiple antennas. This means that, when transmitting a smartphone using an antenna, one of the other unused antennas can transmit simultaneously to other devices such as tablets, smart TVs, laptops or other smartphones. It operates in the downstream direction, AP to client's end-device, and allows an AP to transmit to multiple client devices simultaneously. Certainly, most of the traffic flows are in the downlink direction, so DL-MU-MIMO helps with the most pressing problem.

Before, with the SU-MIMO, the other antennas would remain inactive until the data transmission to the smartphone was complete. So, with an average household using more than seven devices that are simultaneously fighting for bandwidth, MU-MIMO allows the wireless network to run more efficiently and improves not only the Wi-Fi speed, but also the number of devices that can to be connected to the AP.

The MU-MIMO technology work much faster than those without (SU-MIMO), because all devices connected to the wireless network are waiting a shorter time to retrieve data from the Wi-Fi AP. MU-MIMO technology increases the capacity and efficiency of the AP, enabling the network to manage more bandwidth-hungry Wi-Fi activities, such as streaming data and online games. This differs from SU-MIMO in which an AP transmits to a single client device at a time very quickly and efficiently.

The 802.11ac Wave 2 standard limits itself to communicate with a maximum of four clients at a time, using up to a total of eight spatial streams (for all clients) or a maximum of four spatial streams per client in a MU-MIMO transmission. So, an AP can transmit to two clients with one spatial stream each (1+1), or four spatial streams to each (4+4), or four clients each with two spatial streams (2+2+2+2), or some irregular combination (such as 1+2+3 or 2+3+3). It is impossible for the AP to transmit more spatial streams than it has antennas, and even then, it is better to use one antenna for extra reliability, and not for an extra stream. So, a four-antenna AP will likely support only 1+1, 1+1+1, and 1+2 combinations, leaving an antenna inactive.

NOTE: When talking about MU-MIMO systems, it is often left out to talk about the limitation of spatial streams of the end-devices. Nowadays, more or less 70% of the end-devices and most smartphones work with one spatial stream only and most of the laptops with two spatial streams (the newest laptops have the hardware to manage three spatial streams). Even if they have the hardware to work with more spatial streams, the devices will not do it because of battery issues. It is purely marketing to talk about four spatial streams since no devices are able to process those many streams. So, the main part of the end-devices will not notice any change between SU-MIMO and MU-MIMO.

4.3.3.7. Beamforming

Beamforming is a way to provide extra gain when there is more antenna than spatial streams. Beamforming is all about focusing a radio frequency signal in a specific direction. Traditionally, the wireless signal was broadcasted in all direction. With beamforming, the AP determines the location of the device and projects a stronger signal in that specific direction.

Beamforming requires MIMO antenna system. It uses a variety of signal processing techniques to broadcast several different signals at different antennas, ensuring that they interfere in a way that stronger the signal in a specific direction (constructive interference).

Beamforming directs energy to one client at a time, whereas MU-MIMO directs energy to one client and steers that energy away from other clients addressed by the MU-MIMO transmission. Then, it directs energy for a second client and steers to the second lot of energy away from the first and subsequent clients (and so forth if there is a third or fourth client). Beamforming radiation pattern is shown in Figure 43, where the beamforming antennas directs the principal lobe to the corresponding user and nulls on the other user's principal lobes.

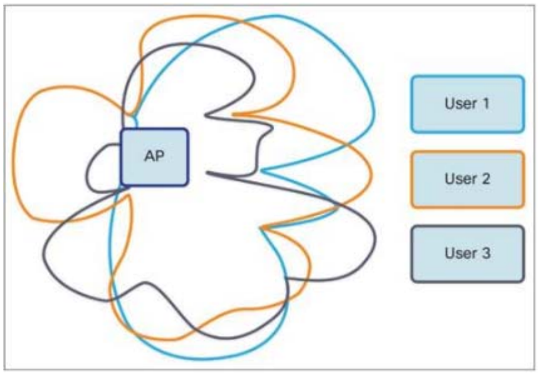

Figure 43 Multiple-User MIMO [39]

There are two types of beamforming: implicit beamforming, which is used for the 802.11n and anterior standard and explicit beamforming, which is used for 802.11ac standard.

4.3.3.7.1. Implicit Beamforming

With implicit beamforming, the AP attempts to use beamforming techniques to improve the signal for older devices, the one without 802.11ac wireless hardware. It does not require support on the part of the client device in order to work, making it universally functional and reducing traffic over the airwaves.

With this technique, the AP will try to localize the client's device, deducing what it can from it. The AP can use the information of the client device to improve the Wi-Fi signal.

It can be used where the AP uses received preambles from the end-device to calculate the beamforming weights, assuming a reciprocal channel. It is used to minimize the amount of overhead.

4.3.3.7.2. Explicit Beamforming

With this technique, a transmitting APs utilize information about communication link with wireless client devices to improve signal transmission to those devices. It provides better reception, range and throughput, while minimizing destructive interferences.

It requires both ends of the wireless link to use the same type of beamforming in the exact same way. Explicit beamforming requires information to be send from the client device to the AP in order to work. The additional information makes the beamforming more accurate; the tradeoff is that it places more data in the airwaves.

4.4. Overall Best Practices

There is a line of work for implementing Wi-Fi networks. Most network features generally follow these practices.

The characteristics that are part of that line of work are the operating bands and channels, the transmitted power and the choice of antennas. The best practice of these characteristics is explained below.

4.4.1. Bands

As explained earlier in this document, the 2.4 GHz band is more limited in the number of non-overlapping channels than the 5 GHz band. Also, the 5 GHz band allows higher capacity since, a 2.4 GHz signal will have 2,4 billion waves per seconds and a 5 GHz signal 5 billion waves per seconds, which is clearly faster.

For this reason, the design of the network will be done for 5 GHz, also because all Wi-Fi developments are on the 5 GHz band and not on the 2.4 GHz (since 2015) due to the fact that the 2.4 GHz band does not provide enough channels and that it suffers from much more interference (too much 'other devices').

The network is going to be implemented in the 5 GHz band and so it will have shorter coverage than in the 2.4 GHz band. This is an advantage because there will be less devices connected to the AP of each cell. The number of devices in a cell increase the risk of collision and the number of retries (business of the channels). Even if the end-device is not connected to the AP but just going through its cell, that end-point will send packet if its radio is turn on.

Still today, many devices in use are limited to 2.4 GHz only. Most if not all 5 GHz devices also have support for 2.4 GHz. Even if the network will be designed for the 5 GHz band, it has to ensure the backward compatibility of the only 2.4 GHz devices. All the APs are dual-band (which means that they can operates at 2.4 GHz and 5 GHz), so they will also support the legacy of the 2.4 GHz clients using previous standards (802.11a/b/g/n).

One issue with the 5 GHz band is that it is more affected by the attenuations than the 2.4 GHz band, so passing through obstacles and walls will introduce a higher attenuation.

4.4.2. Channels and Channel Bonding

The 2.4 GHz spectrum has only 3 non-overlapping channels 1,6 and 11, and that is the only channels that can be used in the whole network at that frequency. Those channels are shown in Figure 2.

In the 5 GHz spectrum there are 25 channel that do not overlap with each other and those are the only channels that can be used. Those channels are shown in Figure 3.

Channel bonding will be configured for the 5 GHz band with a maximum of 40-MHz bandwidth, since there is no need for more and applying a higher bandwidth could cause a lack of bandwidth if many devices were connected.

4.4.3. Power

As seen earlier in the hardware characteristics, the APs and the end-devices do not have the same maximum transmit power, the APs have a higher maximum transmit power than the end-devices.

The maximum power is not recommended to be used because the biggest source of interferences is the neighboring APs on the network. If all the APs of the networks were working at their maximum power, there would be a high co-channel interference due to the APs nearby. Also, the end-device will change its transmit power to reach the one used by the AP. An end-device transmit power affect the fullness of its battery, so working at maximum power will collapse the level of charge of the battery.

The end-devices have lower power than the APs what means that a client that is in the covered area of an AP could not be able to “talk” to him. This provoke the next scenario: there is a client connected to the AP (in its covered area); the AP “talk” loud and the client can “hear” it, but when the client talks, the AP will not hear him since it has a lower transmission power, so the AP will not receive that message and the client will keep retrying. If another client in the same covered area try to transmit, the medium will be busy, and it will not be able to transmit.

A solution using a higher gain antenna could be proposed. It will only create a larger covered area but only downstream (from the AP to the end-device) what will make the problem worst.

A right transmit power should be between 5 dBm and 17 dBm [40]. The lower the transmit power will be, the best it is for the battery of the end-devices. So, the recommended transmit power would be one that matches the end-devices and the AP transmitted power to make the covered area the same for the AP and the end-device and guarantee that the AP and the end-device “hear” each other.

The recommendation on the transmit power at 5 GHz is that it should be half the maximum transmit power of the worst client on the network. So, if the worst client has a maximum transmit power of 11 dBm, the overall transmit power should be 8 dBm (dividing by two in natural units is equivalent to rest 3 dBm).

In the case of this project, the transmission power of the APs will be of 11 dBm, ensuring that the end-device does not work at maximum power.

4.4.4. Cell Overlapping

Since there is every day more devices connected to the Internet, there is a need to support them. To be able to give service to more devices, the cells of Wi-Fi networks have to be each time smaller. But by doing that, the devices have to reconnect more often in order to keep their connection to the network.

For this reason, it is important that nearby APs cells overlap over each other, in order to ease the change of APs while passing from cell to cell. An overlap of 20% of the cell size is recommended for the 5 GHz band.

In the case of this project, the overlapping of cells was not considered because of the high attenuation of the material obstacles. Yet, in the areas of the building with passage, cell overlap of more than 20% is respected.

4.4.5. Antennas

Cisco proposes several different styles of antennas to use with the APs in both 2.4 GHz and 5 GHz bands (dual-band). Each type of antenna will offer different coverage capabilities. As the gain of an antenna increases, there is some tradeoff to its coverage area. Usually high-gain antennas offer longer coverage distances but are not recommended for the reason explained above in the Power Best Practices. The recommendations for the antennas are explained in the Radio Frequency Propagation Indoor part of this document.

In the case of this project, omnidirectional and dipole antennas are presents in the implementation of the network.

The omnidirectional antennas are installed inside the APs with integrated antennas and are used in open offices and hallways. They will be mounted on the ceilings.

The dipole antennas are installed on the APs with external antennas and are used in open offices and hallways. They will be mounted on the ceilings with the antennas straight down or on the walls with the antennas directed with an angle. The dipole antenna chosen has a gain of 4 dBi.

4.4.6. Receiver Sensitivity

The minimum and maximum receiver sensitivity for the APs and end-devices are shown in the Hardware Characteristics part of this document. Nevertheless, these values are limit values to decode the information.

To ensure that all hardware on the network are able to process the data, the receiver sensitivity limit should be set between -67 dBm and -61 dBm.

In this project, a receiver sensitivity of -65 dBm is set for the design, so all devices and APs will be able to decode the received data.

4.4.7. MU-MIMO and Beamforming

The MU-MIMO and beamforming technologies are present in the network. It is not recommended to consider that information in the coverage study since those technologies are enabled only with a certain amount of client devices connected (depends on the 802.11 standard and the hardware).

Nevertheless, it is possible to say that by using MU-MIMO, the transmit power is effectively reduced by 3 dB for each parallel client, since the power is shared amongst all of the parallel streams, while beamforming adds 3 dB to the signal strength for each phased antenna. Also, MU-MIMO systems mainly works downstream, so taking it into consideration will only change the downstream coverage but it does not mean that the client coverage will be the same since only a few client devices integrate the MU-MIMO technology.

Due to the number of people working in this building, only a few APs would be able to activate the MU-MIMO and beamforming technologies, where the amount of people is lower. For this reason, in this project, the power changes due to those technologies will not be considered.

4.5. Wireless Wave's Indoor Attenuations

The recommendation IUT-R P.1238 "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz" methods for the planification of indoor radiocommunication systems and radio local area networks, which is the case of this study [3]. This recommendation will be used to predict the radii of the AP coverage. The tables and formulas used in this study from the IUT-R P.1238 are shown in the Annex 3.

The recommendation IUT-R P.2040 "Effects of building materials and structures on radiowave propagation above about 100 MHz" provides a guide for the attenuation due to material obstructions [4]. The tables and information used in this study from the IUT-R P.1238 are shown in the Annex 4.

To be able to provide the propagation calculus as close to reality as possible, it is important to take all the kinds of indoor wireless wave's attenuations into account. All the propagation losses will reduce the coverage area of the different APs, to be able to provide the desired power at the reception.

From those calculus, it was possible to predict the coverage factor, which ensures that an AP actually cover its calculated radii.

Finally, by measuring the received power using a WiFi Analyzer application downloaded freely on Android, the practical study of the Wi-Fi network was made, including the final calculus and design of the network.

4.5.1. IUT-R P.1238 and IUT-R P.2040

The prediction of the theorical coverage area is based on the IUT-R P.1238 using the site-general model, as it requires little site information. The indoor radio path loss is characterized by both an average path loss and its associated shadow fading statistics.

The model accounts for the loss through multiple floors to allow for such characteristics as frequency reuse between floors. In the case of this study, multiple floors losses will not be taken into account because of the high attenuation between floor. The ceilings include electricity, lightnings and ventilation conducts, which attenuate the signal more than 30 dB (higher attenuation in the 5 GHz band). For this reason, the attenuation through floor is so high that the signal that passes through the ceilings and floors is too weak to interfere. The network will be studied floor by floors.

The distance power loss coefficients include an implicit allowance for transmission through walls and over and through obstacles, and for other loss mechanisms likely to be encountered within a single floor of a building.

In this study, only site-general model has been used to study the behavior of signal strength due to its simplicity. This basic model provides Formula 2 to calculate the total path loss.

$$L_{total} = L(d_0) + N \log_{10} \frac{d}{d_0} + L_f(n) \quad [dB]$$

Formula 2 Basic Model for Indoor Attenuation

Being:

- N: distance power loss coefficient. This value is 31, since the indoor location is an office and the used frequency will be of 5.2 GHz.
- f: frequency (MHz). This value is 5,200 MHz because the network will be designed for the 5 GHz band.
- d: separation distance (m) between the base station and the portable terminal (d > 1m), in other words, the distance of the radii covered by the AP.
- d_0: reference distance (m). This value should be in the range of 1 to 10 meters, in this case the reference distance is 1 meter.

- $L(d_0)$: path loss at d_0 (dB), for a reference distance d_0 at 1 meter, and assuming free-space propagation, can be calculated from: $L(d_0) = 20\log_{10} f - 28$. In this case, with a reference distance of 1 meter and a frequency of 5.200 MHz, $L(d_0) = 46.32\ dB$.
- L_f: floor penetration loss factor. This value will not be considered because this study does not predict the network between floors but floor by floor as explained earlier.
- n: number of floors between base station and portable terminal ($n \geq 0$). At the frequency of 5.2 GHz, only one floor will be affected by the penetration loss.

It can be noted that the distance power coefficient is higher for offices (31) compared to home and commercial area environments (28 or 30). It is due the fact that the office environment is very loud due to presence of people and also the office has a certain interior decor which also absorbs Wi-Fi signals. The office equipment's which are being used e.g. Printer, fax machine, personal computers, telephones and photocopy machines etc. also contribute in effecting the Wi-Fi signals.

4.5.1.1. Shadow Fading

The indoor shadow fading statistics are log-normal, standard deviation values in dB for indoor transmission loss calculation. With an operating frequency of 5.2 GHz and in an office environment, the standard deviation has a value of 12 dB.

The standard deviation will be used to calculate the percentage of coverage zone where the received power is higher than an umbral value, in other words, that the actual received power is higher than the determined value (-65 dBm) in a porcentage of the covered area.

4.5.1.2. Moving Objects and People Attenuation

The movement of people and objects in a room causes temporary variations of indoor propagation characteristics. However, these variations are very slow compared to the data rate used normally and, consequently, can be considered practically as an independent random variable.

Besides, the movement of people in the offices and other places inside and outside the building have a negligible effect on the propagation characteristics. Moreover, the attenuation due to the moving people depends on the moment of the day and the day of the year. It would be very hard to properly evaluate these attenuations.

In conditions without direct visibility, the movement of people near the antennas does not appreciably affect the signal power.

4.5.1.3. Construction Obstacles

Indoor wave propagation is affected by the building material. The density of the material used in the construction of a building determines the number of walls the RF signal can pass through and still maintain adequate coverage. The higher the frequency, the shorter the wavelength is. Shorter wavelengths have more probability to get absorbed and distorted by a building material. So, at a frequency of 5 GHz, the signal will get absorbed highly by the building materials.

Detailed information of the building structure is necessary for the calculation of the indoor field strength, including the different construction materials. Every wall has to be considered. As explained in the Problematic Encountered part of this document, the building dates from the 60's, the plans are not updated, and no one could tell the material used. To be able to calculate the exact attenuation of those obstacles, the measurements have been done manually.

A laptop, equipped with an external antenna, was used with the AirMagnet software to measure the power received. It was moved inch by inch away from the AP in all directions, first with a LOS (Line of Sight) and then with NLOS (Non-Line of Sight) areas of same AP. Initially, the reading was taken every 3 cm which is a quarter wavelength of the Wi-Fi signal approximately, but it was taking too much time and the measuring a single room would have taken in whole day. It was also seen that the signals do not change much for a quarter wavelength, so the step size was increased to half a wavelength (6 cm) but still, the readings were too similar to each other. Finally, a size of a single wavelength was taken for the readings for almost all the location with a step size of 12.5 cm because it is recommended to take readings of one wavelength and if the variations got larger or an abrupt change in the readings in a particular area was seen, then the step would be broken into smaller step size as there can be difference of +/- 6 dBm in readings for a single wavelength step size.

The different material losses encountered measured at 5.2 GHz are shown in Table 11.

Walls	Thin wall	3 dB
	Thick wall	7 dB
	Structure wall	10 dB
Glass Windows	Thin window	3 dB
	Thick window	8 dB
Objets	Medium metal shelf	3,5 dB
	Big metal shelf	9 dB
	Projecting structure	5,5 dB
	Television structure	7 dB

Table 11 Material Attenuations Measured

For comparing loss against obstacles, Table 12 can be used as a reference to see the difference between practical losses and theoretical value. In Table 12, the losses of passing through obstacles reflects the attenuation at the frequency of 2,4 GHz and 5 GHz.

	2.4 GHz	5 GHz
Interior drywall	3-4	3-5
Cubicle wall	2-5	4-9
Wood door (Hollow- Solid)	3-4	6-7
Brick/Concrete wall	6-18	10-30
Glass/Window (not tinted)	2-3	6-8
Double-pane coated glass	13	20
Bullet-proof glass	10	20
Steel/Fire exit door	13-19	25-32

Table 12 Range of Material Attenuations [41]

It was found that practical readings that were taken differ at some places from the theoretical model. It is because IUT-R P.1238 recommendation provides a general model and does not include any factor of obstacle's material that Wi-Fi signal face. Also, these models are empirical models while my work was practical. The path loss coefficient in the recommendation's model includes loss due to walls and in practical study, the path loss coefficient changes according to environment. This model does not contain parameters of reflection and diffraction, as due to reflection and diffraction the signal power can be increased (constructive interference) or can be decreased (destructive interference). For this reason, the IUT-R P.1238 model does not fully work for indoor communication and it shows more losses as compare to practical work.

4.5.1.4. Other Attenuations

From the Annex 2, some additional losses might be considered, depending on the calculus made. These losses appear because of the outdoor-indoor interface [42] and are explained here:

- *Building entry loss*: is the additional loss due to a terminal being inside a building.
- *Shadowing loss*: is the difference between the median of the location variability of the signal level outside the illuminated face of a building and the signal level outside the opposite face of the building at the same height, with multipath fading spatially averaged for both signals.
- *Penetration*: signals outside a building enter an enclosed building by penetration mostly through walls.
- *Aperture penetration*: is the penetration of signals from one side of a wall to the other side through openings on the walls like windows.
- *Building exit loss*: the numerical value of building exit loss will be the same as the building entry loss.

Since there is no outdoor network, the building entry and exit losses are not to be considered since the devices will be disconnected to the AP while being outside and reconnected when entering the building. Moreover, the connection of devices to APs will be limited to a fixed umbral power so outsider could not connect to the network as a security measure. Due to that limited power, by leaving the building, the devices will automatically be disconnected, thus, will not be affected by building entry and exit losses.

The connection of devices will be limited to a umbral power for security measures so the signal's power will be not affected by those losses.

Moreover, the design of the building does not include aperture in the walls, so it has been decided to not take into account those losses.

Finally, the shadowing fading and the wall penetration have been included in the main study of the indoor losses. The wall penetration is added according to the configuration of the building and the different materials the signal passes through.

4.5.2. Theorical Study of An Improved Wi-Fi Network

The theorical study of the coverage of each model of AP must consider the different data explained until now. Those are:

- The transmit power: 11 dBm
- The transmitter's antenna gain: depends on the AP model
- The frequency band: 5 GHz
- The received power: -65 dBm
- The receiver's antenna gain: 3 dBi
- The total losses that include:
  - Basic indoor losses
  - Obstacle losses

From the losses above, the calculus of the different APs coverage distance can be made. The coverage radii calculated will correspond to the downstream coverage (from the AP to the end-device). Because of the equilibration of the power transmitted by the AP and the end-device, the downstream coverage will be equal to the upstream coverage.

After obtaining the radii of the coverage, the probability that the calculated radii could be smaller than expected will be obtained, providing the data needed to calculate the coverage factor.

4.5.2.1. Total Losses and Corresponding Radii of Coverage

To obtain a received power of -65 dBm from the transmit power of 11 dBm, depending on the material losses on the path and on the used AP, the distance of coverage will vary.

Formula 3 will allow to obtain the maximum path loss for each material and AP model:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{total\_max} \ [dBm]$$

Formula 3 Maximum Path Loss

Being:

- P_{RX}: received power at the end-device (dBm).
- P_{TX}: transmitted power from the AP (dBm).
- G_{RX}: gain of the received antenna at the end-device (dB).
- G_{TX}: gain of the transmitted antenna at the AP (dB).
- L_{total}: total path loss (dB).
- L_{total_max}: the maximum path loss to guarantee the received power of – 65 dBm.

So, depending on the gain of the received antenna, the maximum total losses are calculated from Formula 3 and shown in Table 13:

Transmitter Antenna Gain	Maximum Allowed Path Loss
4 dBi	83 dB
5 dBi	84 dB
6 dBi	85 dB

Table 13 Maximum Path Loss Depending on the Transmittr Antenna Gain

From those maximums allow path losses, the maximum distance of coverage can be obtained using Formula 2 that, depending the material losses, provides the maximum distance:

$$L_{total} = L(d_0) + N\log_{10}\frac{d}{d_0} + L_f(n) + L_{material} = 46{,}32 + 31\log_{10} d_{max} + L_{material}[dB]$$

Formula 4 Total Path Losses

Table 14 regroups the different maximum radii of coverage depending on the material losses measured in the building:

Material loss	Transmitter Antenna Gain		
	4 dBi	5 dBi	6 dBi
none	15,2465 (meters)	16,422 (meters)	17,688 (meters)
3 dB (thin wall/window)	12,201 (meters)	13,1418 (meters)	14,155 (meters)
7 dB (thick wall)	9,065 (meters)	9,7638 (meters)	10,5167 (meters)
10 dB (structure wall)	7,254 (meters)	7,8136 (meters)	8,4160 (meters)
8 dB (thick window)	8,416 (meters)	9,045 (meters)	9,7639 (meters)

Table 14 Radii of Coverage Depending on the Transmitter Antenna Gain and the Material Loss at 5 GHz

NOTE: a complete table of the material losses can be found in the Annex 5, containing all the combination of material loss used in the calculation on the distance of coverage for the whole building coverage.

4.5.2.2. Coverage Factor

The coverage factor allows to predict which part of the covered area is actually covered. The distances calculated as the covered radii are not guaranteed, the AP could radiate smaller cells than expected.

To be able to calculate the value of the coverage factor, the probability that the received power is smaller than expected must be calculated (higher signal power).

4.5.1. Probability to Receive a Higher Power Than the Umbral at the Covered Dsitance

To begin with the calculation of the probability to receive a highr power than the umbral at the covered distance must be established previously. In this case, we will suppose that the probability is 75%.

Secondly, the calculated power must be obtained from the distance previously calculated (Table 14). This can be calculated by Formula 5.

$$P(P_{RX} > U) = \frac{1}{2} \times erfc\left[\frac{U - P_{calculated}}{\sqrt{2}\ \times \sigma}\right] \times 100\ \ [\%]$$

Formula 5 Probability to Receive a Higher Power Than the Umbral at the Covered Distance

Being:

- U: umbral chosen to be the received power (-65 dBm).
- $P_{calculated}$: mean received power (in dBm) from the distances that can be found in Table 14.
- σ: standard deviation (12 dB).
- $erfc$: complementary error function.

The maximum covered distance can be calculated by following the next steps:

1. Find the value of the complementary error function associated with the established probabilities.
2. Calculate the corresponding mean received received by applying Formula 5.
3. From $P_{calculated}$ and the umbral power established in the second step, calculate the covered distance by using Formula 3 and Formula 4.

Those steps and the corresponding results are reflected in Table 15 for a 4 dBi gain transmitted antenna and a null material loss.

P(Prx > U)	75%
U (dBm)	-65
Pcal (dBm)	-56,9061229
Ptx (dBm)	11
Gtx (dBi)	4
Grx (dBi)	3
20log(f) - 28 (dB)	46,32
31log(dcob) (dB)	28,5861229
dcob (m)	8,35858952

Table 15 Calculation from the Probability of Signal Strength to the Distance of Coverage

From the calculated distance of coverage (dcob), it is now possible to obtain the coverage factor using Formula 6:

$$Coverage\ Factor = \frac{\pi \times dcob^2}{(\pi^2 \times \frac{dAPs}{2})^2} \times 100\ (\%)$$

Formula 6 Coverage Factor

Being:

- $dcob$: covered distance calculated to ensure a probability of receiving the expected power of 75%.
- $\frac{dAPs}{2}$: distance between two APs divided by 2. This distance is different in each case. This value is going to be, in most cases, around 0,9 of the covered distance. Because of the 20% rule of the overlapping, the $dAPs = 2 \times dcob - 0.2 \times dcob = 1.8 \times dcob$, so $\frac{dAPs}{2} = 0.9 \times dcob$.

Finally, the coverage factor can be written as:

$$Coverage\ Factor = \frac{\pi \times dcob^2}{(\pi \times 0.9 \times dcob)^2} \times 100 = \frac{1}{\pi \times 0.9^2} \times 100 = 39{,}29\%.$$

This result means that only a 40% of the calculated coverage is actually covered by one channel. In the 2.4 GHz band there are 3 non-overlapping channels, which cover 120% of the calculated coverage, confirming that there is a certain degree of overlap between APs coverage.

4.5.3. Practical Study of An Improved Wi-Fi Network

After calculating the distance covered by the APs theoretically, it is now the moment to prove that those calculations are true and validated with real measurements.

First, the covered distance will be practically measured and the probability of receiving the expected power will be reviewed corresponding to the practical distances covered.

Once the covered distances are calculated, the design on the plan of the building can be implemented.

4.5.3.1. *Coverage Factor*

From the theorical study realized, measurements have been done to guarantee that the established value of the probability and the covered distance correspond to the measurements.

The actual measured distance covered in the condition of no material loss is 10,81 meters for a received power of -61 dBm.

The conclusion of those measurements is that the probability established should be lower, because the distance covered are actually much higher than calculated for the probability of 75%.

The values of distances covered have been calculated for probabilities of 70%, 60%, 55% and 50% and are shown in the next table (Table 16):

P(U > Pcal)	70%	60%	55%	50%
erfc's function	-0,370807	-0,179143	-0,088856	-0,0001
U (dBm)	-61	-61	-61	-61
Pcal (dBm)	-54,70719	-57,95983	-59,49206	-60,9983
Ptx (dBm)	11	11	11	11
Gtx (dBi)	4	4	4	4
Grx (dBi)	3	3	3	3
20log(f)-28 (dB)	46,32	46,32	46,32	46,32
31 log(dcob) (dB)	26,38719	29,63983	31,17206	32,678303
dcob (m)	7,099043	9,039069	10,12862	18,65421

Table 16 Calculation of Distance of Coverage for Different Probabilities of Signal Strength

From Table 16, it can be easily seen that the probability that reflects best the reality is a probability of 50%. Since there is no better prediction than reality, the probability of receiving the expected power will drop to 50%.

Finally, the coverage factor will remain the same since the relation between the covered distance and the distance between two APs remains the same. So, the value of the coverage factor is 39,29%.

4.5.3.2. *Design of the Wi-Fi Network at 5 GHz*

The design of the Wi-Fi network has been made on the building plans and can be found in the blueprints joined, excluding the television studios, which are still under testing.

On the plans, the APs coverage is shown by arrows centered at a point. The center of the arrows is the AP location. The arrows go in different direction, facing different obstacles through their way, guaranteeing a coverage in all directions.

NOTE: any covered area can change depending on the transmitted power, the frequency and the data rate allowed. The dependence of the data rate with the cell coverage is shown in Figure 44, where it can be seen that using more complex modulation (the more throughput), the less covered area will be.

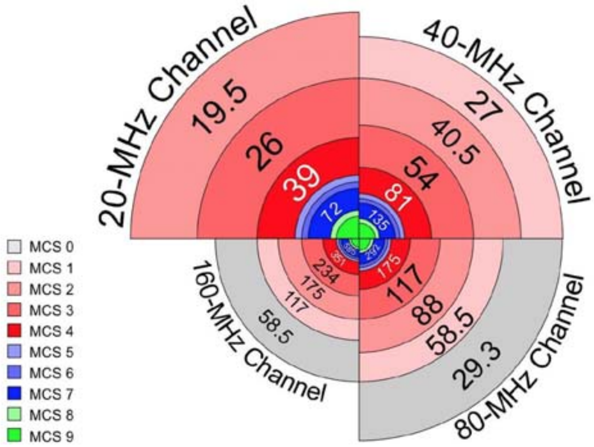

Figure 44 Data Rates and Coverage Distances Depending on the Bandwidth and Modulation [43]

4.5.3.3. Design of the Wi-Fi Network at 2,4 GHz

To be able to provide full legacy of the different standards, a Wi-Fi network at 2.4 GHz must be designed. This design is the same that the one made for the 5 GHz band but removing some APs since the coverage area increase and the attenuation due to material obstacles is lower as the frequency decreases.

From the design of the Wi-Fi network at 5 GHz, some APs will operate in the 5 GHz band only while other APs will operate in dual-band, providing a Wi-Fi network at 2.4 GHz.

The plans of the building for the 2.4 GHz band can be found in the blueprints joined.

The covered distance at 2.4 GHz have been calculated the same way than it has been done for the 5 GHz band and Table 17 regroups the different maximum radii of coverage depending on the material losses found in the building:

Material loss	Transmitter Antenna Gain		
	4 dBi	5 dBi	6 dBi
none	25,1078 (meters)	27,044 (meters)	29,1289 (meters)
3 dB (thin wall/window)	20,0925 (meters)	21,642 (meters)	23,31 (meters)
7 dB (thick wall)	14,928 (meters)	16,079 (meters)	17,3188 (meters)
10 dB (structure wall)	11,946 (meters)	10,867 (meters)	13,859 (meters)
8 dB (thick window)	13,8594 (meters)	14,928 (meters)	16,079 (meters)

Table 17 Radii of Coverage Depending on the Transmitter Antenna Gain and the Material Loss at 2.4 GHz

NOTE: a complete table of the material losses can be found in the Annex 5, containing all the combination of material loss used in the calculation on the distance of coverage for the whole building.

NOTE: the attenuation due to the material obstruction have very small difference with the ones calculated for the 5 GHz band, so the same values are used.

4.5.3.4. Conclusion

For the whole building coverage, the number of APs are, by model:

- Serie 2600 with external antennas: 5
- Serie 2700 with external antennas: 9
- Serie 2700 with internal antennas: 47
- Serie 2800 with external antennas: 153
- Serie 2800 with internal antennas: 7
- Serie 3600 with internal antennas: 9

The total number of APs is 229. The enterprise is missing 68 2800E model AP to be able to implement the complete Wi-Fi network designed.

Finally, a list of the different used APs, their location in the building and their operating band in shown in Annex 6, with a list of the number of needed APs of each model.

5. New Wireless Technologies

The wireless communications world moves very fast, with new technologies announced each year. Wi-Fi is also subject to rapid changes with the 802.11ac wave standard new on the market.

With the rapid increase in the number of connected devices each day and the introduction of the IoT, it is very clear that the future of wireless communication is doubtless. The success of wireless systems continues to grow, with 4G/LTE and soon 5G.

Regarding the future building of the RTBF, two new wireless technologies will be explained. One of them is the Li-Fi [44], which is a wireless communication system that uses light to transmit data and the other technology is the latest Wi-fi standard, 802.11ax [45].

5.1. Light Fidelity (Li-Fi)

The Li-Fi is a wireless data transmission system that uses light as a communication vector. The principle of Li-Fi is based on two important points, the reuse of existing technologies and the benefits of visible light.

Li-Fi relies on the existing light, such as the light we use for lightning. Li-Fi modifies this use to also transmit information digitally at very high speed invisibly. For these high-speed communications, Li-Fi uses LEDs, which have many advantages: very large switching capacity, robustness, low consumption, long life, …

Many technologies already use visible light to communicate and they are grouped under the name of VLC (Visible Light Communication) technology, which is the case of the Li-Fi technology. Today, communications are mainly transmitted via the electromagnetic spectrum. However, this means that the communication is not always the best. The visible domain has many advantages over the latter: much larger spectrum, important security, almost non-existent use in terms of communication …

The large spectrum of the visible domain, shown in Figure 45, is the portion of electromagnetic spectrumthat is visible to the human eye. A human eye will respond to wavelengths from about 390 to 700 nanometers, which corresponds, in terms of frequency, to a band from 430 to 770 THz.

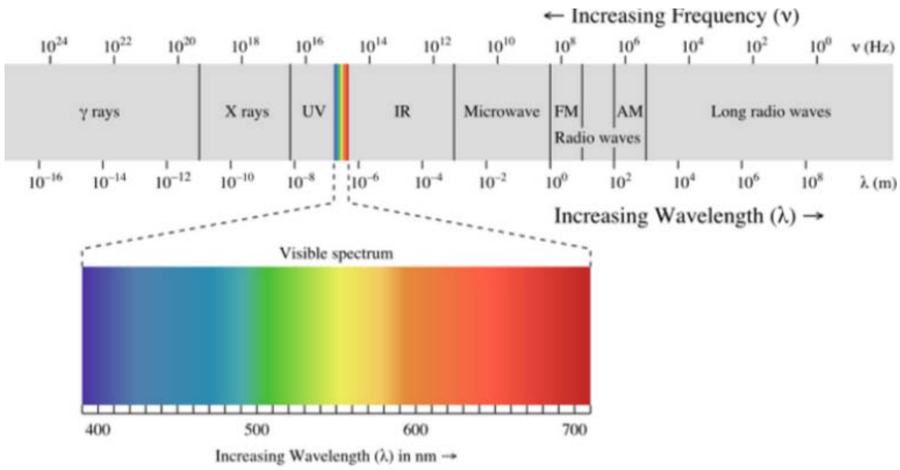

Figure 45 Spectrum of Visible Domain [44]

To be able to communicate via Li-Fi, some operations must be processed and specific hardware must be installed in the devices (end-points and APs). The operations are explained from the two end sides, the transmitter and the receiver.

5.1.1. Transmitter

In order to transmit the information, the transmitter can use different possibilities, such as a white LED. LEDs have many advantages and as far as the lightning power is concerned, the LED lamps have not yet arrived at the maximum of their possibilities. The Figure 46 shows the exponential evolution of the luminous power of LEDs from the 70's to 2000. In this range of time, the luminous power emitted increased more than by 10.000 times.

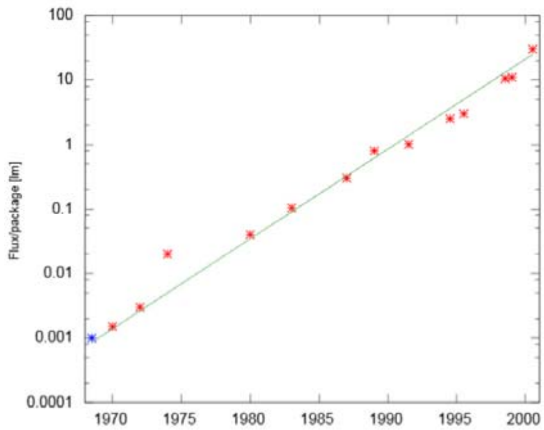

Figure 46 Evolution of the LED Light Power with Time [44]

Another possibility is to use RGB triplets (red, green, blue) which are more expensive than the previous technology due to the use of three LEDs instead of one. RGB triplets are also accounting with multiplexing in order to increase the data transfer rate.

The rate of transmitted data can be increased by other techniques such as the MIMO technology explained in the Multiple Antenna Systems part.

5.1.2. Receiver

The receivers for the Li-Fi technology are simple to design with a relatively wide bandwidth and a good resistance to noise [46].

Regarding communication, two choices are possible for the laptop, smartphones and tablets: either directly integrate these receivers into the device, or to have a module to receive the information and transform it in order to exploit it. Once the data is received by the photodetector, it must be decrypted in order to retrieve the useful information.

Concretely, photodiodes are used. These photodiodes receive the light containing the information, then decode somehow the information in order to retrieve the useful information. Then, the received information must be decrypted. The reverse process must be done to recover the original signal.

5.1.3. Integration of Li-Fi

Li-Fi has many advantages. However, the main problem to solve is the uploading. Indeed, this technology allow to receive data, it cannot allow to send data [46]. The Li-Fi can obviously be adapted to send data by equipping all the devices with a Li-Fi transceiver but it increases costs considerably. Moreover, Wi-Fi can be a solution for upstream flows, but it would make the use of Li-Fi superfluous.

5.1.4. Possible Uses

The Li-Fi technology allows to offer a range of possibilities for all types of domains. Some use cases are explained to better understand the impact that such a technology could have on today’s and tomorrow’s communication.

5.1.4.1. Geolocalisation

Li-Fi could be used to orient users inside building. Li-Fi can manage the localization with a precision of about 10 cm and a response time of about 10 milliseconds against a few meters and a few seconds for existing localization technologies [44].

5.1.4.2. Sensitive Infrastructures

Li-Fi is one of the wireless solutions that would equip aircraft and hospitals, because this technology can not pose a problem of interference with the various electronic devices already in place.

5.1.4.3. Automobile

It is thanks to this sector of activity that the Li-Fi was born [44]. The purpose of Li-Fi in this area is to communicate using LED headlighting of the car with all road elements or vehicle to facilitate the journey of drivers.

5.1.4.4. Targeted Information

LED lights in large areas or the backlight of advertising LED screen can be used to send specials or advertisements to customers. In museums, it would be possible to access on his smartphone to the explanation of a work by placing himself under the lightning of this one.

5.1.4.5. Connected City

The Li-Fi being developed thanks to the lightning and electrical networks of the city, it would be possible to obtain a lot of information on the daily life of the city (transport, maintenance, tourism).

5.1.5. Conclusion

By using visible light, Li-Fi communications could be implemented in most places. This is an advantage that only VLC technologies can have.

The Li-Fi technology is revolutionary, offering many uses. As of today, very few devices can receive and send information via Li-Fi. The necessary transceivers in the devices are not yet quite widespread. In addition, a shadow between the light and the devices implies a loss of communication, which is an irreversible disadvantage.

Due to the problematic drawbacks, it is not possible to imagine implementing such a technology in order to provide a wireless transmission system inside a new building since no device would be able to communicate via Li-Fi.

5.2. 802.11ax

By the end of 2018 – beginnings of 2019, a new 802.11 standard will be introduced, 802.11ax. It promises a "smart" wireless communication, able to adapt to the conditions of use.

The main mission of 802.11ax will be to optimize the quality of connections in very dense environments such as public places (railway stations, shopping malls, airports, stadiums, office buildings, …). In these conditions of high network congestion, the data rate could be multiplied by four comparted to the data rate offered by the current standards [47]. Again, these predictions are based on the MU-MIMO technology which is not yet widely deployed on end-devices.

The 802.11ax, also called High Efficiency WLAN (HEW), will be an evolution of 802.11ac which, like its ancestor will operate in the 2.4 GHz and the 5 GHz bands. In order to enable the uplink multi-user data transmission, 802.11ax borrows from the technologies used for the 4G/LTE mobile cellular connection.

Last February, Qualcomm unveiled two 802.11ax-compatible chips for APs and end-devices [47]. The precise information on the performance to be expected is still rather vague and subject to change. At the moment, Qualcomm is talking about 4.8 Gbps in maximum throughput (compared to 1.3 Gbps with 802.11ac).

5.2.1. Principles

802.11ax is based on four principles [48], all used to optimize user connection speed:

1. The OFDMA (OFDM Access) is a technology directly inspired by the current 4G. The main idea is to modulate the rates according to what the user needs. With the OFDM system, the allocated data rate remained fixed even if only a small packet of data was sent in. With the OFDMA, one well-filled wider bandwidth will be used for the users instead of using three narrower bandwidths for each user, in other words, only one well-filled truck is used for the three users, and not three trucks of the same size. As a result, free space is available on the bandwidth for users who really need it.

In a Wi-Fi connection, a frequency band used to transmit data is composed of multiple sub-carriers. Instead of assigning a complete frequency band to a single user, the OFDM access will share the sub-carriers between several clients. In order to increase the number of people likely to share the same channel, the radio spectrum between the subcarriers is shrunk from 312 kHz currently at 78 kHz for 802.11ax. The result is that 802.11ax will have the same bandwidth as 802.11ac (20, 40, 80 and 160-MHz), but with a frequency space four times lower between its subcarriers. For example, 9 clients can be added simultaneously on a 20-MHz channel, 18 customers on a 40-MHz channel, 37 customers on an 80-MHz channel and 74 customers on a 160-MHz channel.

2. MU-MIMO, compared to the current standards, would increase the number of antennas to serve eight users at a time (against four nowadays). Thus, each of them will benefit from its dedicated antenna, determined accordingly to where it is in the room. Each user’s device will retrieve information describing the status of their connection, both in download and upload, thus improving the coverage even if it is the antenna best adapted to the position of the user that will be used.

The number of antennas present on transmitters and receivers goes from 4x4 to 8x8. Each user will be allocated the best performing antenna according to their physical position relative to the AP.

3. The Uplink Resource Scheduler, again inherited from the 4G standard, makes it possible to organize and prioritize the data uploaded by each user, whereas they were previously in frontal competition to send their data to the router. This ends traffic jams to the router; the flows of connections are better organized and do not wisp down as before. In the end, and according to Qualcomm’s explanations, 802.11ax will be able to adapt the connection rate according to the type of use for each user sharing a channel depending on whether the user is watching a stream video or chatting on instant messaging.

4. The Target Wakeup Time (TWT) is a clever new way to limit disturbances between different Wi-Fi networks. If the AP is not solicited, it will go to sleep to stop transmitting. This reduces the average level of interference.

5.2.2. Conclusion

It is obvious that the new 802.11 standard will be used in the near future. The principles used for the implementation of 802.11ax allows those networks to be “smart” and to change parameters depending of the use of the network.

Nevertheless, the information about 802.11ax is still ringing and the wait, before the devices can access this technology, is still long. All end-devices and APs must be equipped with modules adapting the device to the new standard. Still, it is probable that the new building will be using this new technology.

Finally, the theorical data rate announced are not yet achievable in the “real world”. The MU-MIMO technology will need to be practically improved in order to increase the number of antennas on the end-devices.

6. Implementation of a Wi-Fi Network for an "Intelligent" Building

The RTBF is currently building a new building, whose construction will finish in January 2022. As a part of this project, it was proposed to study possible solutions to implement an "intelligent" building. To be able to provide the different solutions, it is important to understand what is an "intelligent" building, and which are the risks and advantages of such systems.

For the creation of a new wireless network for this new building, several questions were asked about the technology to use. Given the upcoming release of the 5G, the usefulness of a Wi-Fi network has been called into question, as it would be possible to directly install 5G terminals. In response to these questions, it has been chosen not to work on a public network but on a private network.

On one hand because the characteristics of the 5G network are very vague (exact operating frequency and technique not yet revealed) and it is not possible to make any theorical study on those terms but also because it will be 2023 before a 5G network could be fully implemented and functional.

On another hand because the 5G network is a public network it means that it is externally managed. By using a private network, such as Wi-Fi, a team can be monitoring security breaches and the whole network is under the control of the enterprise.

Finally, a Wi-Fi theorical study of the new building will provide a range of number of APs needed in order to implement an optimized Wi-Fi network.

6.1. Understanding of "Intelligent" Buildings

An "intelligent" building could be defined as a building that integrates technologies, where the combination of technologies and interconnected systems supports the building's users use and provide the efficient operation of the building. Also, it must be enabling the possible space reconfiguration, depending on the changing uses.

The core building systems technology has materially changed lately creating both risk and opportunity for new developments. These changes have occurred and continue to occur faster than the traditional real estate support structure. For these reasons, smart building processes might be created in order to automate processes and manage the risks of the implementation.

The different systems that could be implemented in an "intelligent" building can be divided into diverse utilities with their corresponding uses:

- Infrastructure of the building: sensors, IP network, wireless, data rooms, server rooms, …
- Building Systems: building management system, access control, lightning control, fire alarm, water management, waste management, …
- ICT (Information and Communication Technology) Systems: office automation (e-mail, data, Internet), media-multimedia (voice, video, music), IP-based applications, …
- Business Systems: enterprise resource planning, integrated services/helpdesks, …

6.1.1. Advantages

The integrated use of systems and technologies delivers a commercial advantage. For example, the convergence of the network infrastructure enables the flexible use of accommodations, and operational efficiency arise from the integration of systems which support or manage the building environment, space and operational systems.

The infrastructure convergence is typically achieved through the use of a common cabling and/or wireless infrastructure, supporting IP-based networks within the building. Thus, the building management systems will typically use an open protocol running over an IP-based network for all data acquisition and control functions.

The advantages of using a converged infrastructure include:

- A workplace that can be used more efficiently and effectively, by making the use of space more flexible and reducing the cost of churn.
- The ability to reconfigure access control and security systems to reflect changing use or to enable multiple occupancy.
- Self-service access to facilities management tools by the building occupants from their office computers.

The integration of systems may occur on two level:

- The integration of building systems and ICT systems; or
- The integration of both building systems and ICT systems with business systems.

The advantages that are provided will depend on the level of integration. An example in an office environment is the use of "smart" building passes to manage access to printer and photocopying services.

Similarly, when a user logs on to a desktop computer, it may trigger the automatic association of an adjacent desktop telephone with the user's extension number. This integrated approach can lead to a reduction of workspace reconfiguration costs as the users are no longer tied to specific workstations. To improve the energy efficiency, systems may be integrated to internal monitoring of the "smart" building passes to determine when an area is no longer occupied. The building management system may then be configured to allow energy-saving measures to be automatically implemented, such as reducing lightning and air conditioning.

6.1.2. Risks

The introduction of a converged infrastructure and integration of building and business systems potentially creates a range of new risks associated with aspects of the personnel, technology and operations.

The human elements of the building operations are potentially the greatest risk. Whether deliberately or accidentally, individuals may seek to bypass security controls or incorrectly operate systems. The integration of systems can magnify the impact of errors or omissions. System integration will bright together IT (Information Technologies) and facilities management teams who may have different priorities, cultures and reporting chains. All of these can inhibit an effective response to incidents or faults.

From a technology perspective, integration may introduce new failure modes, where building systems can interfere with business systems and vice versa. For example, it is normal for office computers to run the latest antivirus software and be regularly patched. This may not be true for the computers used for safety-critical systems, thus leading to potential vulnerabilities from malware introduced over the network or from infected media.

The use of IP-based technologies creates opportunities for operational savings through the centralizing and outsourcing of control and monitoring stations. But this can lead to a loss of local knowledge and control. The problem is exacerbated if the support personnel are only deployed in response to incidents as they may not be familiar with the layout and operation of individual buildings.

6.1.2.1. Avoid the Risks

As such the risks associated with people, systems and operations need to be appropriately managed and mitigated. The people risks will arise from four constituencies:

1. *The designers:* they need to be aware of, and have mitigated the potential consequences of, actions by third parties, whether they are support contractors with legitimate remote access to systems or unconnected partied with a malicious or hostile intent.
2. *The building owners*: they need to consider what degree of systems integration is required and-or desirable during the specification, design, construction and commissioning of the building.
3. *The building operators*: the daily tasks and responsibilities of the "intelligent" building facilities manager and technicians need to be clearly defined and include a clear understanding of the complexity of integrated systems.
4. *The building occupants and visitors:* they may need to be informed about the correct and safe operation of building systems.

6.1.3. Conclusion

"Intelligent" buildings are a relatively new and evolving area, so there is a need for buildings owners and occupiers to ensure that the novel risks are fully understood and addressed throughout the building lifestyle.

In an enterprise as large as the RTBF is, it is imperative to be able to automate and centralize a maximum of processes, measures and systems and to be able to reconfigure them as needed.

6.2. Hardware Characteristics

Due to the fact that the construction of the building will end in 2022, it is difficult to know with certainty what hardware will be used for the different devices since the wireless communication technologies are constantly evolving. For this reason, assumptions have been made to be able to rely on certain characteristics to perform the network coverage calculations.

For the APs, the latest Cisco APs released in 2018 will be used for as a base information for the antenna gain, receiver sensitivity and transmit power.

For the Wi-Fi module, a few characteristics might be supposed from the use of today's end-devices.

6.2.1. Access Points

The last release of Cisco APs includes different series: 1815 series, 1830 series, 1850 series and 4800 series. All of these series allow legacy for 802.11a/b/g/n/ac wave 2 standards.

The 1815 series is targeted for small or midsize enterprise deployment and propose four slightly different models whose differences make no difference in the theorical coverage study. The 1815 series provide a 2x2 MU-MIMO with two spatial streams technology and also the beamforming technology downstream.

The 1830 series is also targeted for small or midsize enterprise deployment. It provides a 3x3 MU-MIMO technology with two spatial streams for the 802.11ac wave 2 devices. For the other standards, only the SU-MIMO technology is allowed, transmitting data to only one client at a time. The 1830 series provides transmit beamforming technology that improves downlink performance to mobile devices, including one and two spatial stream devices on 802.11ac, while improving battery life on mobile devices such as smartphones and tablets.

The 1850 series, targeted for small or midsize enterprise deployment, provides a 4x4 MU-MIMO technology with four spatial streams when operating in SU-MIMO mode and three spatial streams while operating in MU-MIMO mode. The MU-MIMO mode is used only with the 802.11ac wave 2 standard while the other standards will work in SU-MIMO mode. The 1850 series also provides transmit beamforming technology that improves downlink performance.

Finally, the 4800 series is targeting large enterprise organizations requiring mission-critical traffic. This AP model provides a beamforming technology in both upstream and downstream directions. They are packed with an abundance of features that offer users a better experience, top-notch security and high-speed connectivity. The AP functionality is spread out over four internal radios. The 4800 series expands the current rich capabilities with features such as built-in Flexible Radio Assignment, Hyperlocation and BLE (Bluetooth Low Energy) and adds a fourth internal radio to provide rich performance and location and security analytics. With more radios embedded in the AP, the wireless network achieves higher security and data analysis without degrading performance.

Having a fourth radio allows the BLE and security monitoring functions to run on their own individual radios, while the other two radios tend to the business of providing exceptional Wi-Fi. This level of visibility provides IT more powerful capabilities to help ensure the user experience for productivity and engagement.

Depending on the model and the series, the antenna gain changes. All the antenna gain for the latest Cisco APs are shown in Table 18.

Frequency Band	Series 1815				Series 1830	Series 1850	Series 4800
	1815i	1815m	1815t	1815w			
2,4 GHz	2 dBi	2 dBi	2 dBi	2 dBi	3 dBi	3 dBi	2,5 dBi
5 GHz	4 dBi	4 dBi	3 dBi	3 dBi	5 dBi	5 dBi	5 dBi
5GHz only	-	-	-	-	-	-	3,5 dBi

Table 18 Antenna Gain of the Cisco 1815, 1830, 1850, 4800 Series Access Points [49]

For a channel bonding of maximum 40-MHz, none of these APs receiver sensitivities would be higher than the recommended reception signal of -65 dBm. Concerning the transmitting power, the power level goes from -1 dBm to 20 dBm.

For the creation of a new Wi-Fi network, the models chosen are the 4800 series and the 1850 series. For the building areas, the 4800 series APs were chosen because of all the new features offered by Cisco. It is an AP with integrated antennas (omnidirectional). For the parking areas, the 1850 series was favored because of the antenna gain and technologies included. This model is available with external antennas (directional) or integrated antennas (omnidirectional).

6.2.2. End-Point Wi-Fi Modules

The characteristics that are more likely to evolve through the year concerning the end-points Wi-Fi modules are the antenna gain, the receiver sensitivity and the transmitting power.

Concerning the antennas gain, it is possible that their value changes over through the years. However, their values will stay in a rather low range, between 2 and 5 dBi. These values will not change drastically because they must correspond, more or less, to the value of the antenna gain of the devices with which they will connect. The value chosen for the antenna gain of the end-device is 3 dBi. Even though it is a supposition, a difference of one dBi in those coverage ranges will only make a difference of approximately one meter and a half, which is not an enormous variation to actualize in the calculations.

The receiver sensitivity is another characteristic that will change over the years. Depending on the channel bonding, the codification and the modulation used, the receiver sensitivity changes. With more complex modulations and codifications it is possible to reach higher data rates, but the receiver sensitivity will be higher in order to decode properly the transmitted data. But what increase the receiver sensitivity most is the channel bonding. For example, using the same MCS index and the same frequency, a 20-MHz channel will have a sensitivity of -72 dBm while with a 40-MHz channel of -68 dBm. In other words, a wider channel will be more sensitive than a narrower channel.

Finally, the transmitting power the end-point devices could change with the innovation of batteries lifetime. One of the biggest problems of the end-devices is their battery life which is the main reason of the limitation of the transmitting power of the devices. It can be seen that batteries charging times have already increase significantly in the recent years and it can be imagined that this technology will continue to evolve in this direction. For this reason, assuming that nowadays the end-devices transmit at a power of 11 dBm, in a few years they could be transmitting at 14 dBm. For this reason, the theorical study of a new Wi-Fi network will be studied for a transmitting power of 14 dBm.

6.3. Theorical Study of a Wi-Fi Network

For the new building Wi-Fi implementation, the theorical study of the coverage will have to consider the different characteristics of the hardware explained until now. Those are:

- The transmit power: 14 dBm
- The transmitter's antenna gain: depends on the AP model
- The frequency band: 5 GHz
- The received power: -65 dBm
- The receiver's antenna gain: 3 dBi
- The total losses that include:
    - Basic indoor losses
    - Obstacle losses

The losses to take into account will be the same as the ones considered for the implementation of the Wi-Fi network for the current building which can be find in the Wireless Indoor Attenuation part of this document.

From the total losses, the calculus of the different APs coverages can be made. The calculated coverage will correspond to the downstream coverages (from the AP to the end-device).

After obtaining the radii of the coverage, the probability that the calculated radii could be smaller than expected will be obtained, providing the data needed to calculate the coverage factor.

6.3.1. Total Losses and Corresponding Radii of Coverage

Based on the recommendation IUT-R P.1238, the maximum path losses can be calculated considering the different indoor attenuations. The site-general model is used in order to calculate the losses due to the indoor environment. Formula 2 was used to obtain the value of those losses.

Then, to obtain a received power of -65 dBm from the transmit power of 14 dBm, depending on the material losses on the path, the distance of coverage will vary.

Formula 7 will allow to obtain the maximum path loss, which includes the indoor attenuation and the construction obstacle losses:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{total\_max} \ [dBm]$$

Formula 7 Maximum Path Loss

Being:

- P_{RX}: received power at the end-device (dBm).
- P_{TX}: transmitted power from the AP (dBm).
- G_{RX}: gain of the received antenna at the end-device (dB).
- G_{TX}: gain of the transmitted antenna at the AP (dB).
- L_{total}: total path loss (dB).
- L_{total_max}: the maximum path loss to guarantee the received power of – 65 dBm.

Depending on the gain of the received antenna, the maximum total losses are calculated and shown in Table 19:

Transmitter Antenna Gain	Maximum Allowed Path Loss
5 dBi	87 dB
4 dBi	86 dB
3,5 dBi	85,5 dB

Table 19 Maximum Path Loss Depending on the Transmitter Antenna Gain

From those maximums allowed path losses, the maximum distance of coverage can be obtained from the Formula 8 which considers the material losses:

$$L_{total} = L(d_0) + N \log_{10} \frac{d}{d_0} + L_f(n) + L_{material} = 46{,}32 - 31 \log_{10} d_{max} + L_{material} [dB]$$

Formula 8 Total Path Losses

Table 20 regroups the different maximum radii of coverage depending on the material losses found in the building:

Material loss	Transmitter Antenna Gain		
	3,5 dBi	4 dBi	5 dBi
none	18,3576 (meters)	19,0522 (meters)	20,5212 (meters)
3 dB (thin wall/window)	14,6907 (meters)	15,2465 (meters)	16,422 (meters)
7 dB (thick wall)	10,9147(meters)	11,3276 (meters)	12,201 (meters)
10 dB (structure wall)	8,7344 (meters)	9,0649 (meters)	9,7639 (meters)
8 dB (thick window)	10,1333 (meters)	10,5167 (meters)	11,3276 (meters)

Table 20 Radii of Coverage Depending on the Transmitter Antenna Gain and the Material Loss

NOTE: due to the lack of information, the material losses depends on the functionality of the building's zone and the suppositions based on the actual building material losses measures.

6.3.2. Coverage Factor

As seen in the theorical study of a Wi-Fi network for the current building, the coverage factor is a parameter that permits to predict how much of the covered area is actually covered. The distance of coverage calculated in Table 20 are not always valid, and the coverage factor allows to estimate the actual covered distance as a percentage of the total covered area.

To be able to calculate the value of the coverage factor, the probability that the received power is higher than the sensitivity must be calculated.

6.3.2.1. Probability to Receive a Higher Power Than the Umbral at the Covered Distance

During the practical study of a Wi-Fi improved network for the current building, the values assigned to the probability to receive a higher power than the sensitivity, that will be considered in this section, are 70% and 50%.

Concerning the theorical study of a Wi-Fi network for the new building, in which it is not possible to make reception signal measurements, the number of APs necessary for the building full coverage will be in a range of values. This range will be limited by the worst case (higher number of APs) and the best case (lower number of APs). The worst case has been defined using a probability of 70% and the best case using a probability of 50%.

In order to obtain the mean received power at the covrage distance ($P_{calculated}$), Formula 9 is implemented.

$$P(P_{RX} > U) = \frac{1}{2} \times erfc[\frac{U - P_{calculated}}{\sqrt{2} \times \sigma}] \ [\%]$$

Formula 9 Probability to Receive a Higher Power Than the Umbral at the Covered Distance

Being:

- U: umbral chosen to be the received power (-65 dBm).
- $P_{calculated}$: mean received power at the distances detailed in Table 20 (in dBm).
- σ: standard deviation from the IUT-R P.1238 (dB).
- $erfc$: complementary error function.

The maximum covered distance can be calculated by following the next steps:

1. Find value of the complementary error function associated with the established probabilities.
2. Calculate the corresponding $P_{calculated}$.
3. Apply Forrmula 8 to obtain d_{max}.

Those steps and corresponding calculation are reflected in Table 21 for a 4 dBi gain transmitted antenna and a null material loss for the cases of a probability of 70% and 50%.

P(Prx > U)	70%	50%
U (dBm)	-65	-65
Pcal (dBm)	-58,7072	-64,9983
Ptx (dBm)	14	14
Gtx (dBi)	4	4
Grx (dBi)	3	3
20log(f) - 28 (dB)	46,32	46,32
31log(dcob) (dB)	33,3872	39,6783
dcob (m)	11,94	19,0522

Table 21 Calculation of Distance of Coverage for Different Probabilities of Signal Strength

From the calculated distance of coverage (dcob), it is now possible to obtain the coverage factor with the Formula 10:

$$Coverage\ Factor = \frac{\pi \times dcob^2}{(\pi^2 \times \frac{dAPs}{2})^2}$$

Formula 10 Coverage Factor

Being:

- $dcob$: covered distance detailed in Table 21.
- $\frac{dAPs}{2}$: distance between two APs divided by 2. This distance is different in each case. This value is going to be, in most cases, around 0,9 of the covered distance. Because of the 20% rule of the overlapping, the $dAPs = 2 \times dcob - 0.2 \times dcob = 1.8 \times dcob$, so $\frac{dAPs}{2} = 0.9 \times dcob$.

Finally, the coverage factor can be written as:

$$Coverage\ Factor = \frac{\pi \times dcob^2}{(\pi \times 0.9 \times dcob)^2} = \frac{1}{\pi \times 0.9^2} = 0.3929 = 39{,}29\%.$$

Since the value of overlapping cells remains the same, the coverage factor is equal to the one calculated in the case of the theorical study for the implementation of a Wi-Fi network for the current network.

6.3.3. Design of the Wi-Fi Network at 5 GHz

For the design of the Wi-Fi network at 5 GHz, the 20% cell overlapping was respected. Depending on the zone and predicted material losses, the different covered radii are shown. The design of the Wi-Fi network has been made on the building plans. The worst case (probability of 70%) and the best case (probability of 50%) can be found in the blueprints joined.

On the plans, the APs coverage is shown a circle, being the center of it the theoretical localization of the AP. This design is only made for theorical purpose with the goal of calculating a range of number of needed APs.

NOTE: any covered area can change depending on the transmitted power, the frequency and the data rate allowed. The dependence of the data rate with the cell coverage is shown in Figure 44, where it can be seen that for more complex modulation (the more throughput it gets), the more covered range it gets.

NOTE: no design was implemented for the Wi-Fi network at 2.4 GHz. The reason for this is that the study is not reflecting reality because there is still unknown information about the building plans and materials. This study is only for an information purpose. In time, a study and design must be realized in order to establish the localization of the APs.

For the deign made on the plans for the theorical study of the Wi-Fi network for the new building, some localizations are worth talking about. Those are explained next.

6.3.3.1. Studios

For the television studios, depending on the size of it, one or two APs have been predicted to cover the full area and the potential number of devices connected to them. Because of the soundproofing of those studios no valid signal will be received from the APs inside the studios to the devices outside them.

Because of the reduce number of devices connected and their smaller sizes (compared to television studios), only one AP will be covering each radio studio. Almost no signal will pass through their soundproofed wall but since the studios are smaller, it is possible that devices outside the studios connect to the AP inside the studios.

6.3.3.2. Newsroom

In the new building, the newsroom will be part of the floor’s open space. The ceiling will be made of glass so no AP will be able to be place on it. The coverage of this area will be radiated by the sides. Still, since the plans are still not guaranteed, it is hard to predict how many APs will be needed for this specific area.

Depending on the case, between 2 and 6 APs will be needed.

6.3.3.3. Lifts and Stairs

For the stairs and lifts, it is necessary to ask for recommendation with Cisco to ensure the well coverage of those zones.

A priori, one AP by floor by stair should be more than enough, regardless of the coverage area. Thereby, a total of 39 APs has been calculated for the different staircases of the new building.

For the lifts, if it is possible to place one AP for each elevator, 12 APs would be needed (one by lift).

6.3.3.4. Conclusion

In the best case (with a probability of 50%), a total of 229 APs will be needed for the working areas of the buildings using the 4800 series. For the parking areas, 32 APs will be needed using the 1850 series. The total number of APs needed to cover the whole building will be 261 in the best case.

For the other case, the worst one (with a probability of 70%), a total of 360 APs would need to be place in order to cover the working areas of the building, all of them being of the 4800 series. For the parking areas, a total of 63 1850 series APs will be needed. The full overage of the building would require 423 APs in total for this case.

NOTE: the final number of APs needed for the coverage of the building do not include the lifts and staircases.

7. Conclusion

This part of the document will highlight the various elements to be taken into account during the realization of the implementation of a Wi-Fi network for this network to be efficient, fast and strong. The various aspects discussed below are based on the conclusions made after the study of a Wi-Fi network for the current building of the RTBF as well as the future building of the same enterprise.

When creating a Wi-Fi network design, it is important to understand the different properties of radio waves. These properties allow to characterize the factors that influences these signals in order to provide a robust and reliable network.

For example, the transmission power influences the coverage area of the APs and end-devices. A large difference between the transmit power of the APs and terminals will cause a difference in the coverage area which will imply more retransmissions and black the possible transmission of other devices. Moreover, a transmission power that is too high will have a harmful effect on battery's life time. Another example is the choice of the operation frequency band. The use of each band involves another spectrum, thus other advantages and disadvantages. For the 2,4 GHz band, the coverage distance is wider but the spectrum offers fewer usable channels and is busier due to use of the same band by other technologies. On another hand, the 5 GHz bands offers more channels in exchange of covering lower distances.

The different parameters of the radio waves are the bases of the well-functioning of a Wi-Fi network. The choice of the values of each of the parameters can have a devastating effect just as it can optimize the network. For these reasons, RF wave theory is the basis for implementing a robust, resilient and consistent Wi-Fi network.

Another aspect that must be considered is the importance of the realization of an appropriate site-survey. When carrying out the theoretical study of the implementation of a Wi-Fi network for the current building, certain choices were made concerning the reliability of the coverage distances of the APs. When comparing the results obtained theoretically from predictions and the results obtained from measurements made during the site-survey of the building, a significant difference appeared. No prediction is valid for all cases, a case-by-case study is needed in order to implement a powerful and unfailing Wi-Fi network.

The last point that will be discussed in this part of the document is the importance of characterizing the locations to be covered. Each part of the building has its own specificity. This implies that each office is arranged differently, uses other technologies that might interfere with the Wi-Fi network and is built differently. These different factors attenuate the signal differently and therefore affect the reception signal. Each location is physically different and used by other people, with different venue's frequencies and different uses. It is important to have a good understanding of the area and the use of the different locations to be covered in order to implement a network that is made to last, to adapt to different types of events and to provide capacity and performance to the users.

8. Conditions

The purpose of this section is to describes the necessary conditions for the realization of this End-of-Grade project. These conditions include all the software and hardware requirements that has been essential for the student to achieve this work.

The main hardware condition for the realization of this work is a laptop. The laptop used for this project is the HP EliteBook 1040, with the following specifications:

- Processor: Intel Core i5-7200U with Intel HD620 graphics card
- Operating System: Windows 10 Professional 64
- RAM Memory: 8 GB
- Hard Disk: SSD Storage of 256 GB
- Screen Size: Full HD of 14’’

Using the laptop as the main tool, the student has used the entire Office 2016 package for the development of the project as a support for computonational automation (Excel), for writing the work (Word) and for the presentation of the work (PowerPoint).

Part of the work has been the realization of a full site-survey, which have been carried out using different supports depending on the study achieved. Those supports are the following:

- The Ekahau HeatMapper software has been used for the research of Rogue APs inside the building, providing a map with all the APs encountered.
- The Insider Office software has been used for the measurement of the APs radiations, providing RSSI values for each AP (referred by its name and MAC address).
- The AirMagnet software and accessories (antenna and adaptator antenna-USB) have been used for the measurement of the APs radiations, providing RSSI values for each AP (referred by its name and MAC address).

Two different supports have been used to measure the receiving power of the APs, which ensure that the measurements taken approximate the reality and that the tools used are functional and well calibrated.

Finally, the Cisco Prime software has been used to simulate the lack of coverage of the Wi-Fi network in the Reyers site, and to provide a map with the localization of the existing APs in the building. This support also allows the engineer to have an operational view of the different APs providing a real-time analysis of the network, which is very useful when testing the implementation of the network.

9. Budget Estimation

This last part of the document will evaluate the budget corresponding to the work done for the End-of-Grade project.

Table 22 enumerate the cost of the different materials used for the implementation of this project.

Item	Price
HP EliteBook 1040	1.627,00 €
Ekahau HeatMapper Trial Version	- €
Insider Office Trial Version	- €
Cisco Prime	25.000,00 €
AirMagnet Program	3.259,00 €
AirMagnet Accessories	1.315,00 €
Office 2016	175,59 €
TOTAL	31.376,59 €

Table 22 Material Budget Estimation

Table 23 make an estimation of the costs that would reflect the working hours dedicated to this End-of-Grade Project.

Hours dedicated	Price
One hour of work	18,42 €
5 month, 5 days a week, 7 hours and a half a day	13.815,00 €

Table 23 Personal Budget Estimation

Finally, Table 24 shows the total estimated cost of the End-of-Grade Project.

Material Costs	31.248,59 €
Personal Costs	13.815,00 €
TOTAL	45.063,59 €

Table 24 Total Budget Estimation

10.Blueprints

10.1 Blueprints of the Actual Building at 5 GHz

The arrows represent the coverage of the APs in different and relevant direction. The center of the arrows reprensents the location of the APs.

- Building CHJM

❖ Eleventh Floor

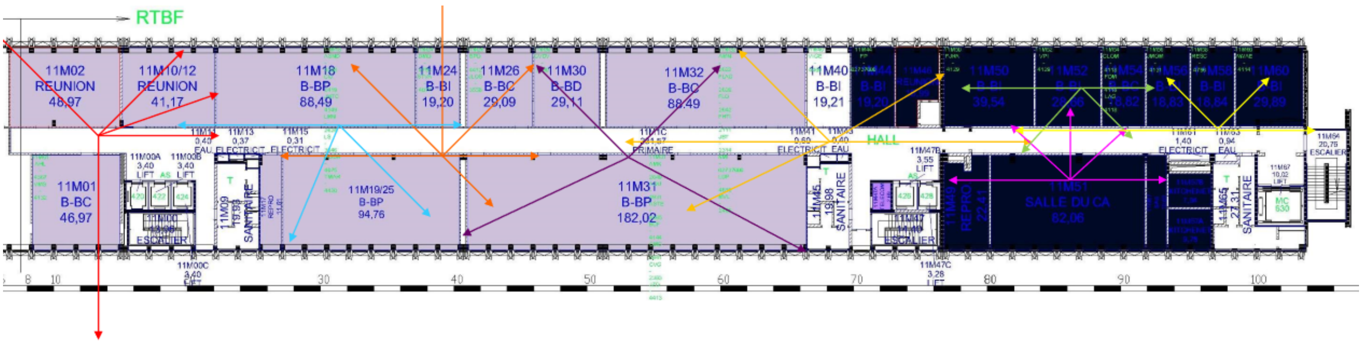

Figure 47 Design at 5 GHz for Floor 11 in Building CHJM

❖ Tenth Floor

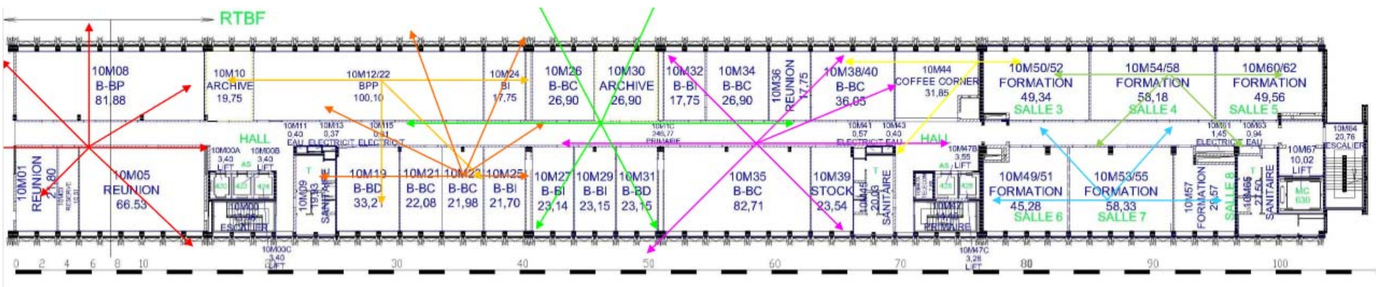

Figure 48 Design at 5 GHz for Floor 10 in Building CHJM

❖ Ninth Floor

Figure 49 Design at 5 GHz for Floor 9 in Building CHJM

❖ Eighth Floor

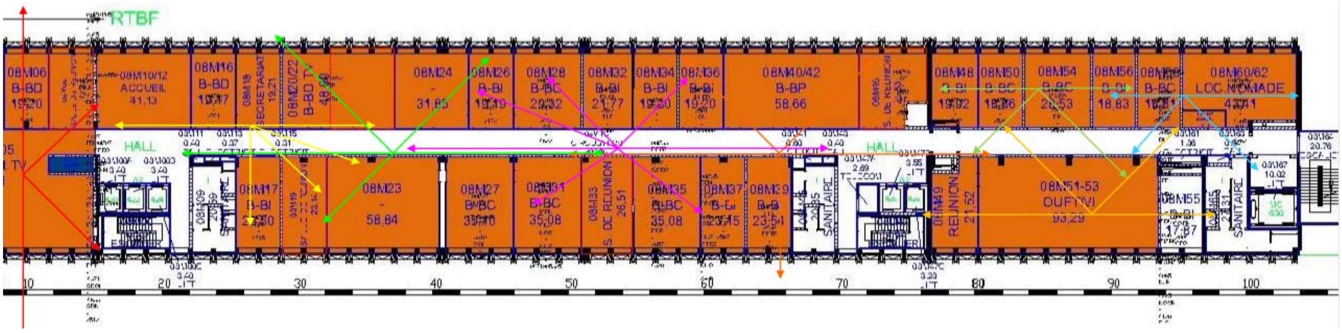

Figure 50 Design at 5 GHz for Floor 8 in Building CHJM

❖ Seventh Floor

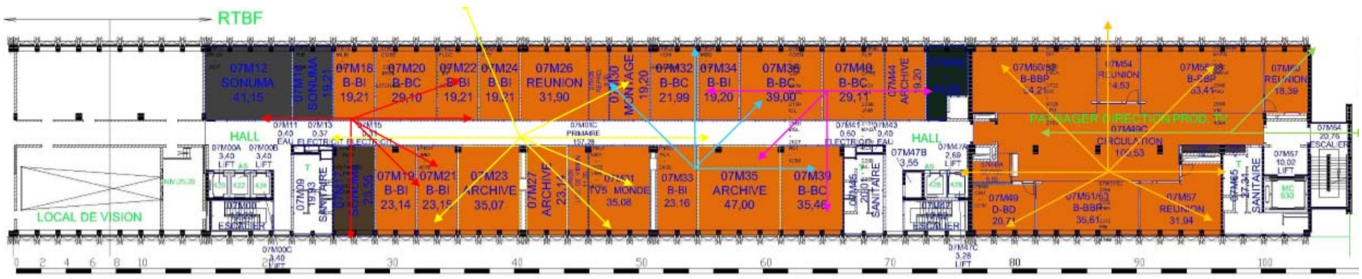

Figure 51 Design at 5 GHz for Floor 7 in Building CHJM

❖ Sixth Floor

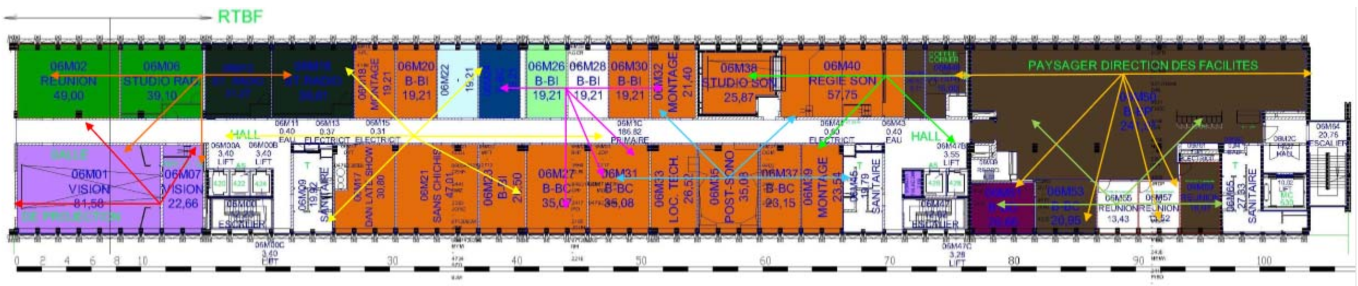

Figure 52 Design at 5 GHz for Floor 6 in Building CHJM

❖ Fifth Floor

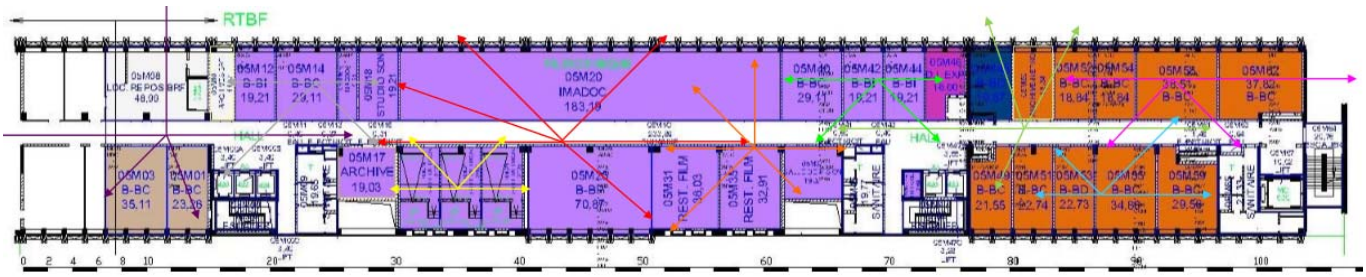

Figure 53 Design at 5 GHz for Floor 5 in Building CHJM

❖ Fourth Floor

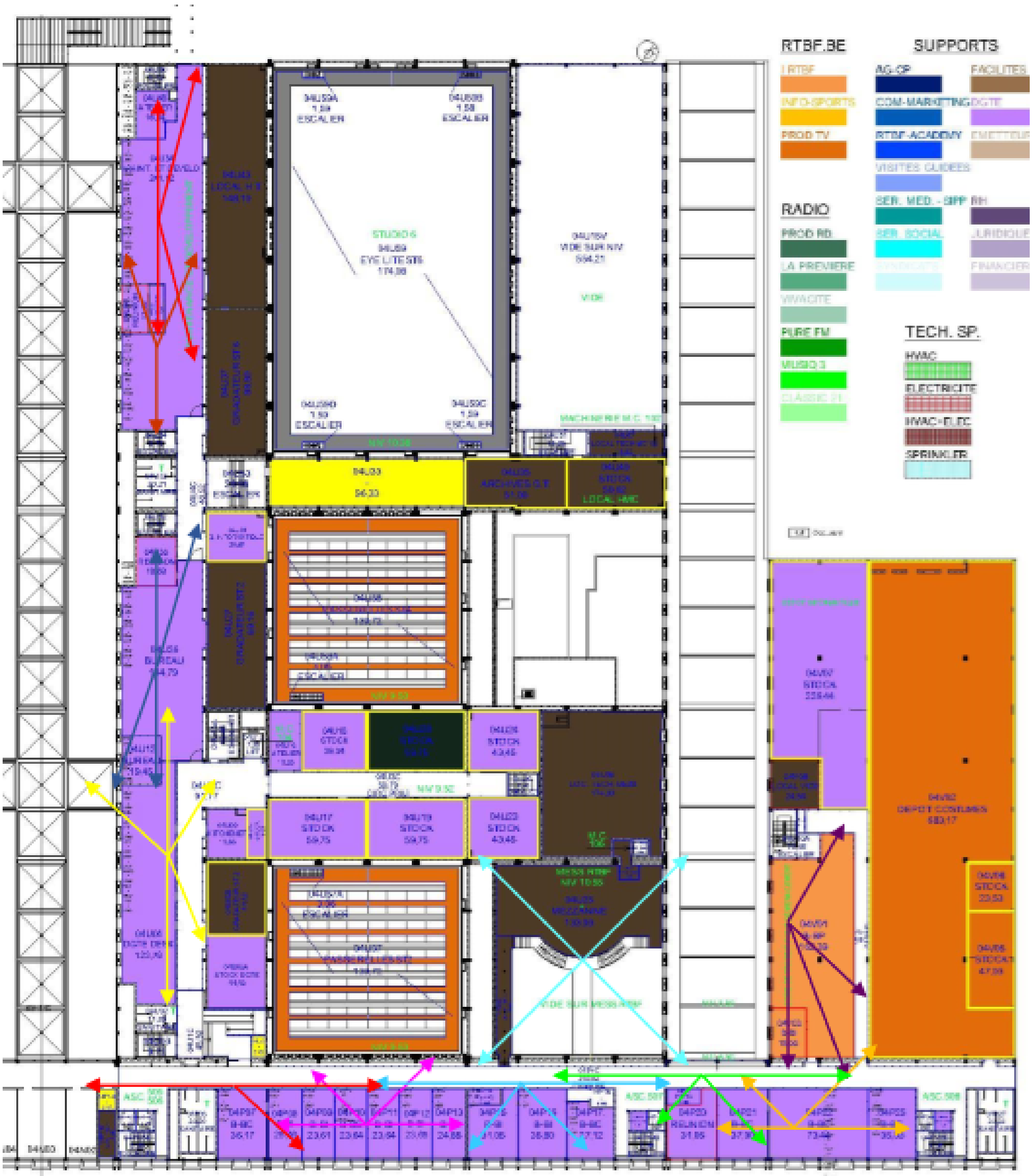

Figure 54 Design at 5 GHz for Floor 4 in Building CHJM

❖ Third Floor

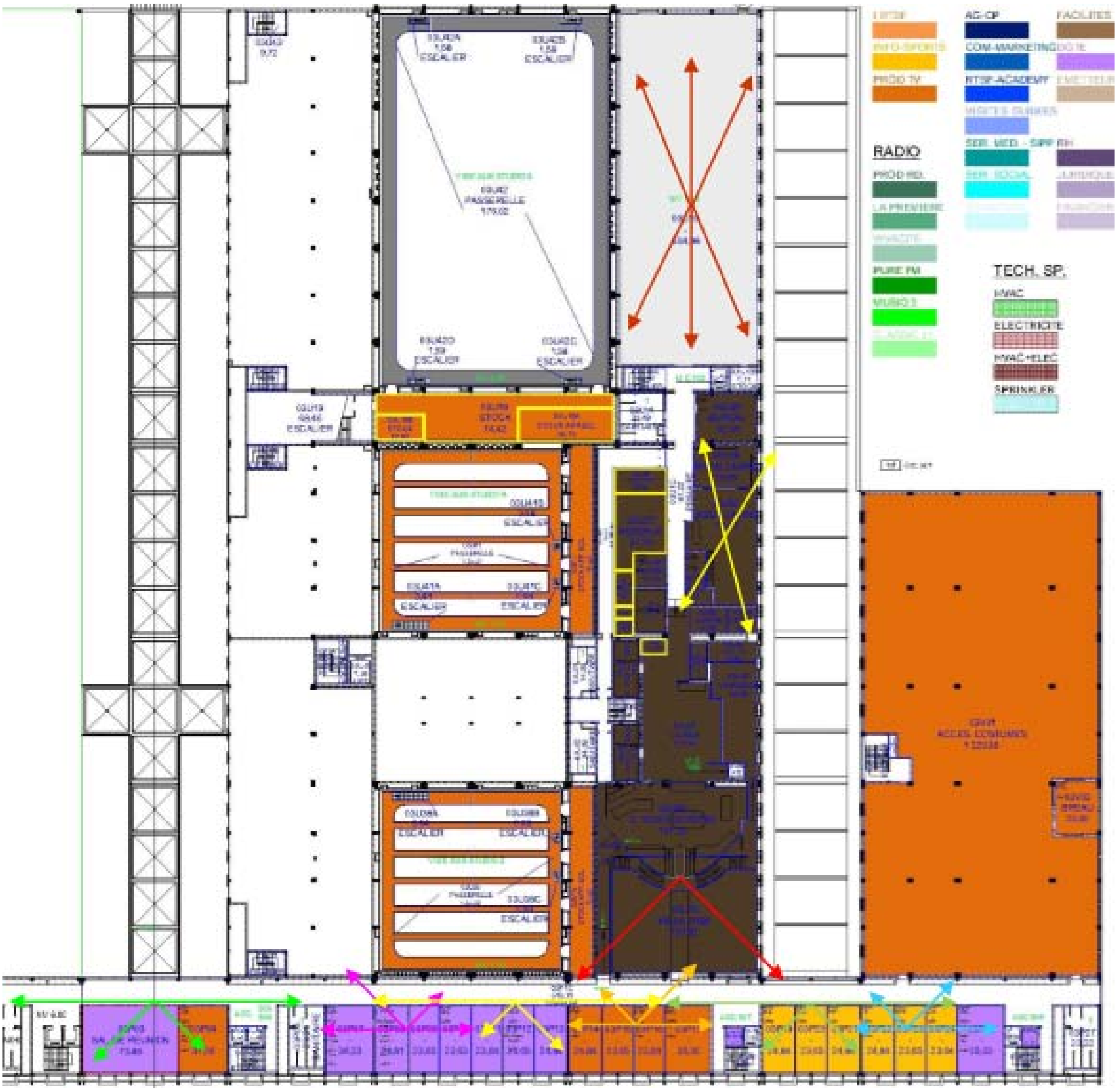

Figure 55 Design at 5 GHz for Floor 3 in Building CHJM

- Second Floor

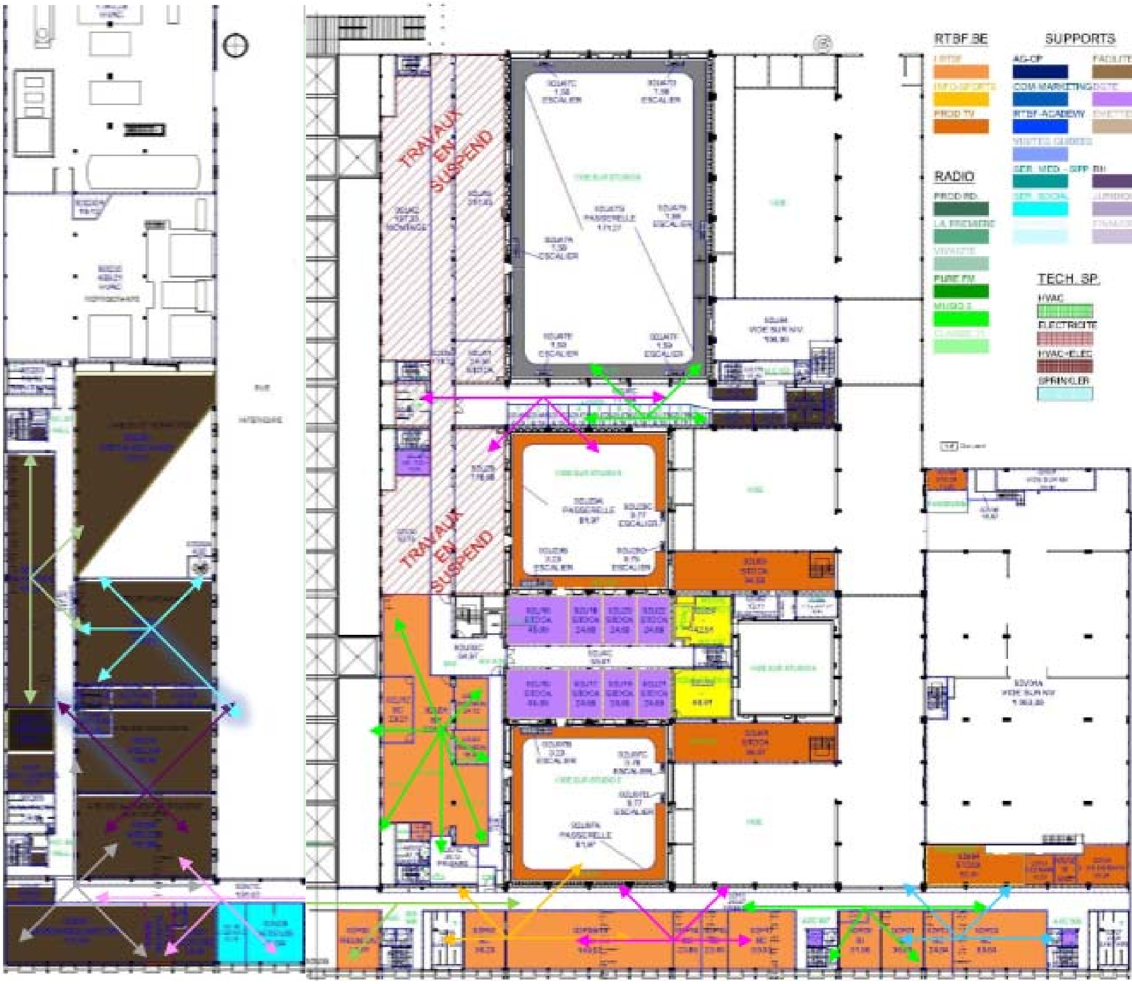

Figure 56 Design at 5 GHz for Floor 2 in Building CHJM

- First Floor

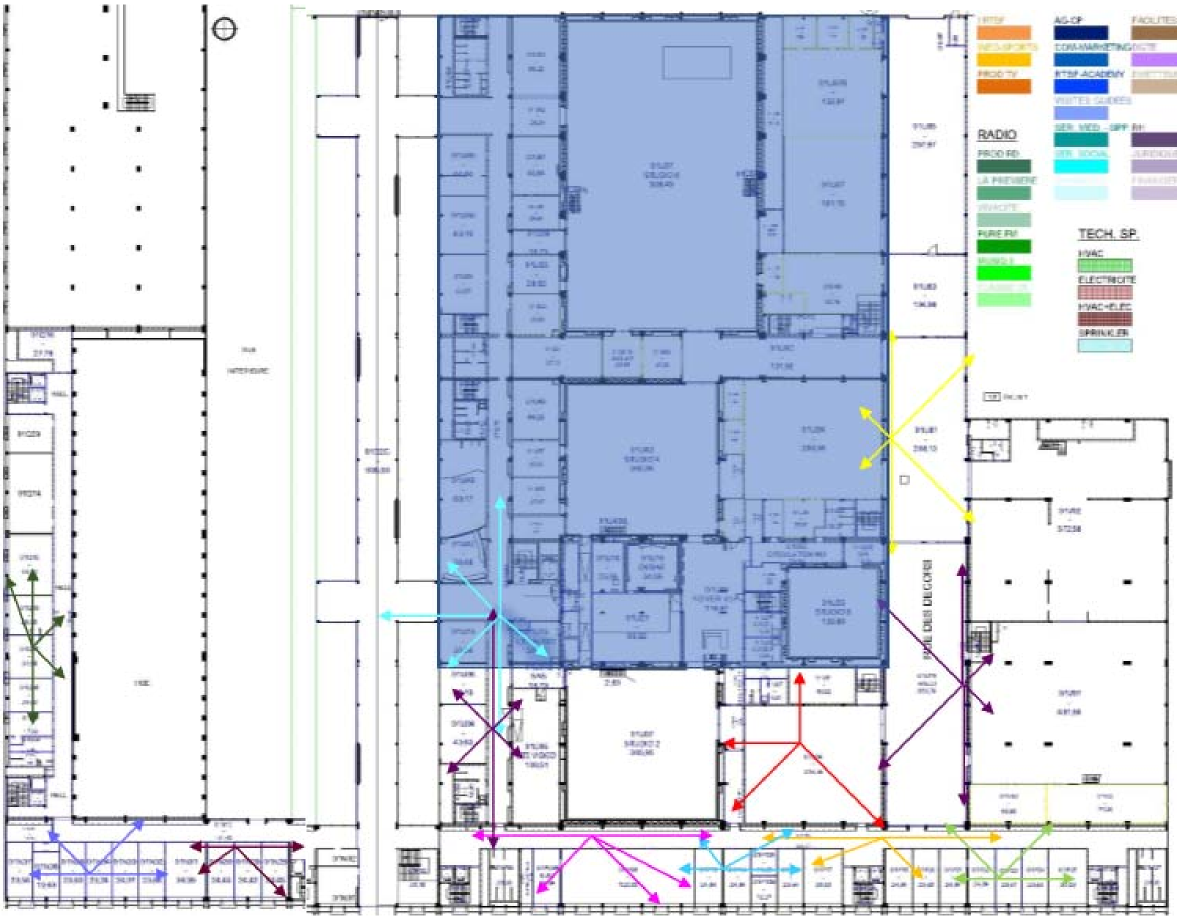

Figure 57 Design at 5 GHz for Floor 1 in Building CHJM

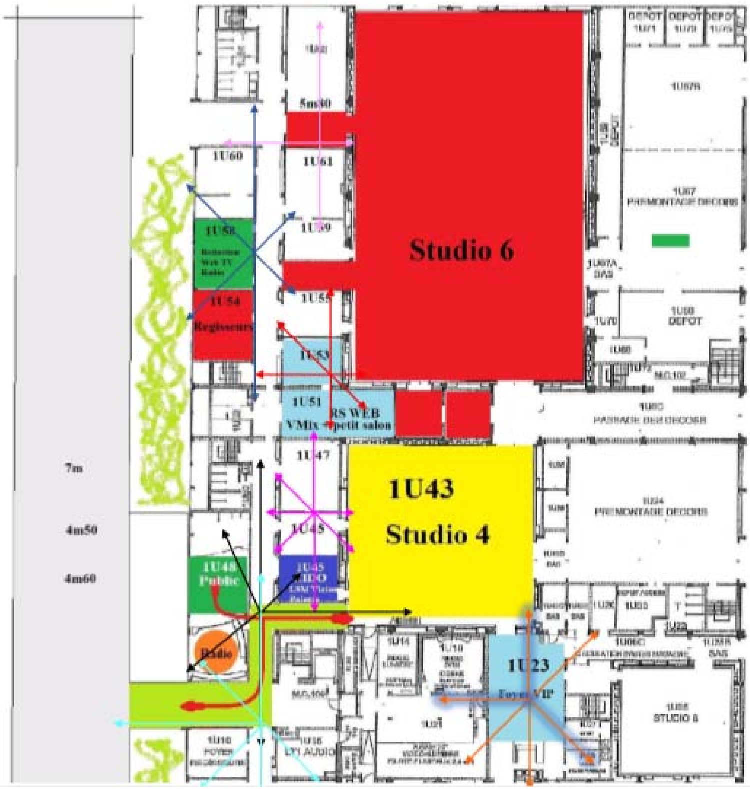

Figure 58 Design at 5 GHz for Floor 1 Television Studios in Building CHJM

❖ Ground Floor

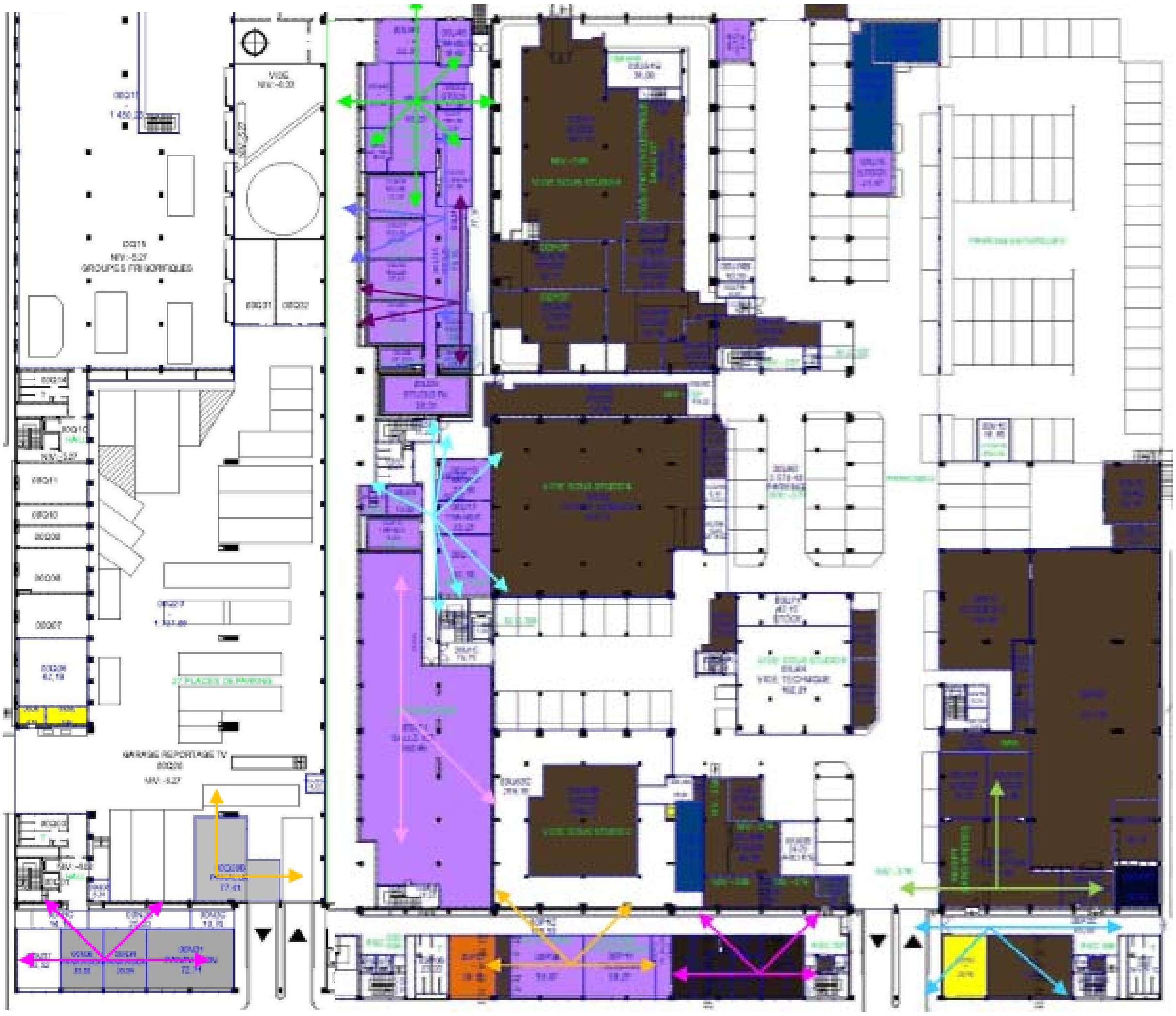

Figure 59 Design at 5 GHz for Ground Floor in Building CHJM

- Building PUVQ

  - ❖ Fourth Floor

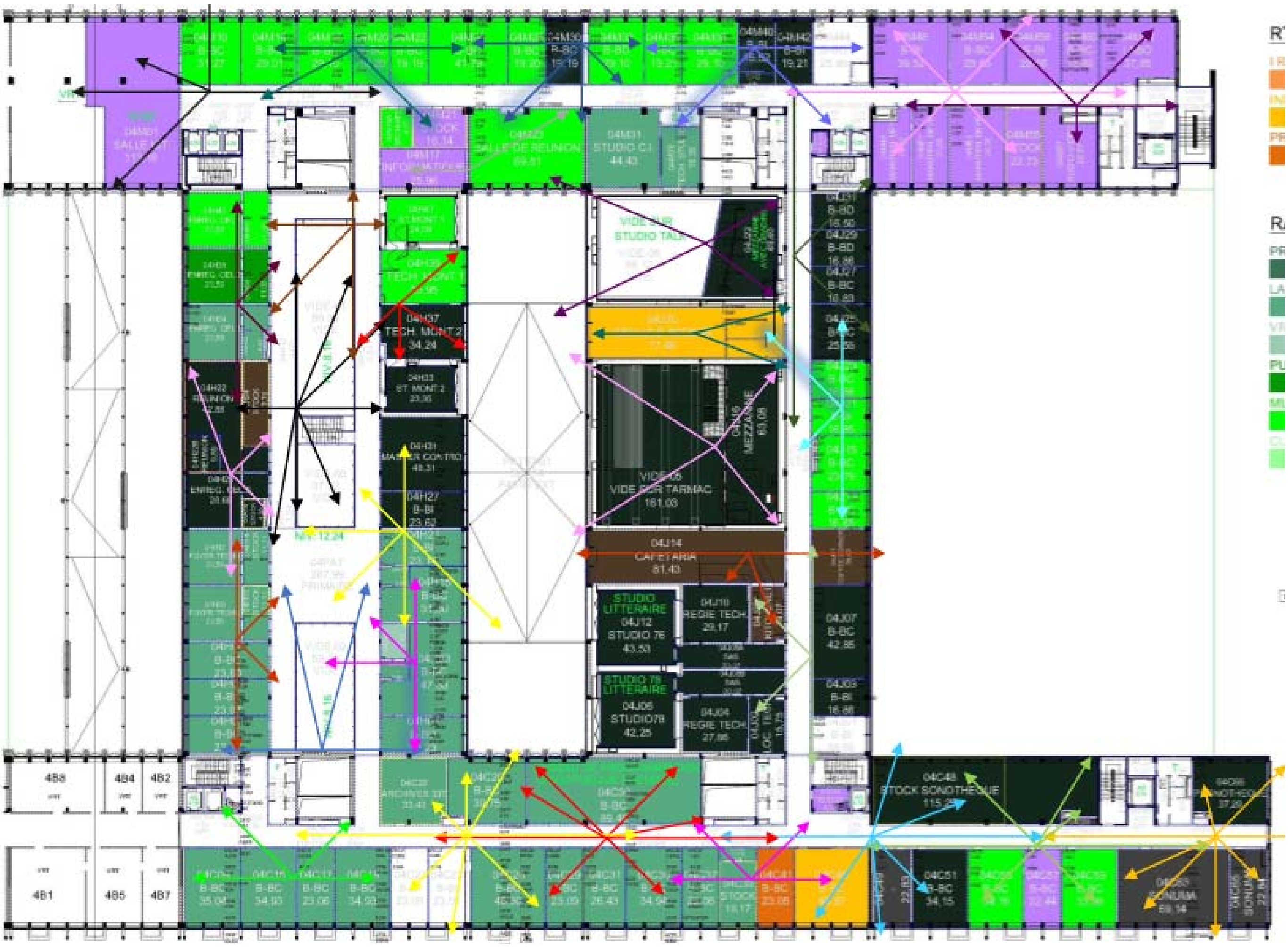

Figure 60 Design at 5 GHz for Floor 4 in Building PUVQ

- Third Floor

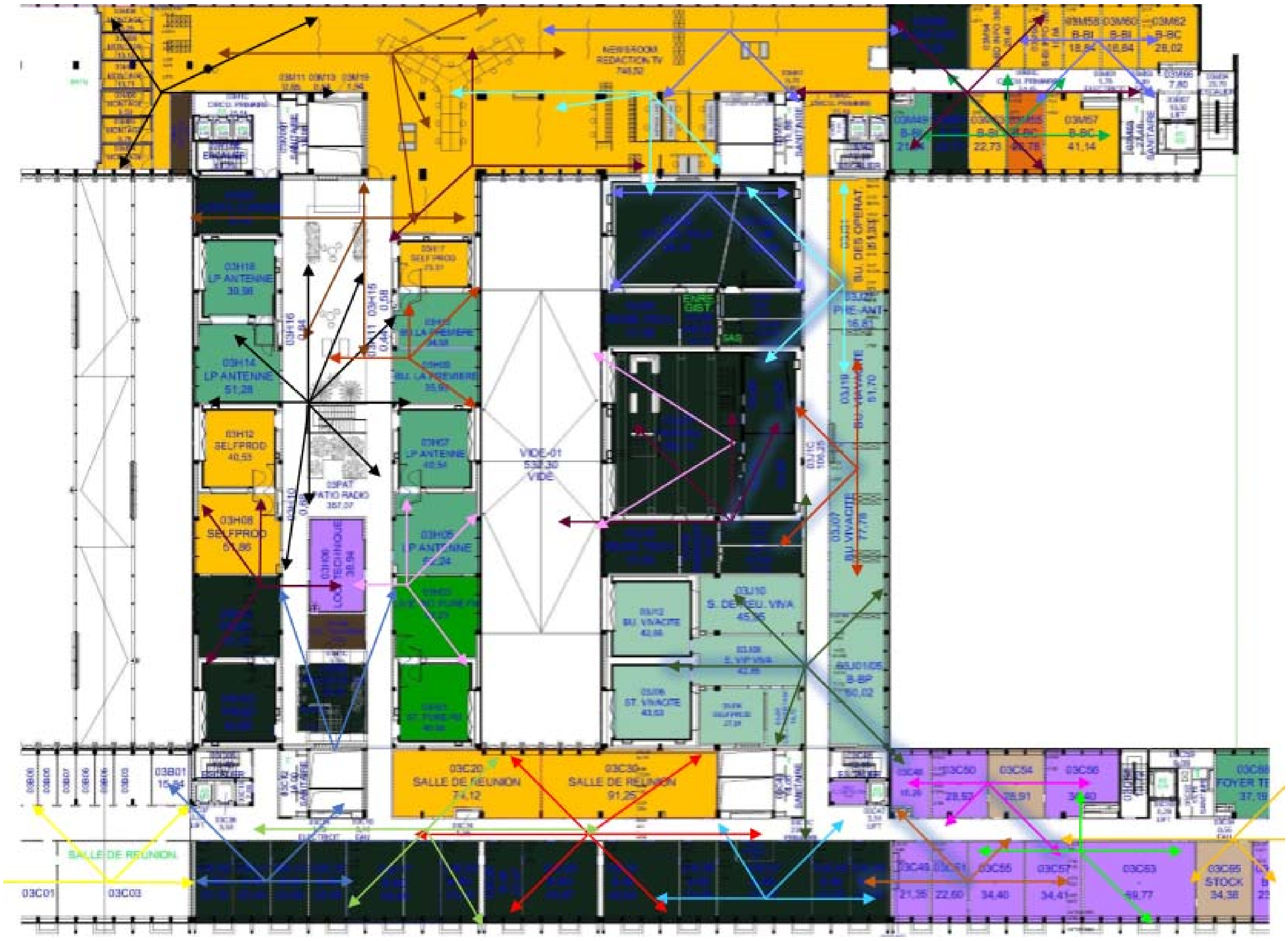

Figure 61 Design at 5 GHz for Floor 3 in Building PUVQ

❖ Second Floor

Figure 62 Design at 5 GHz for Floor 2 in Building PUVQ

❖ First Floor

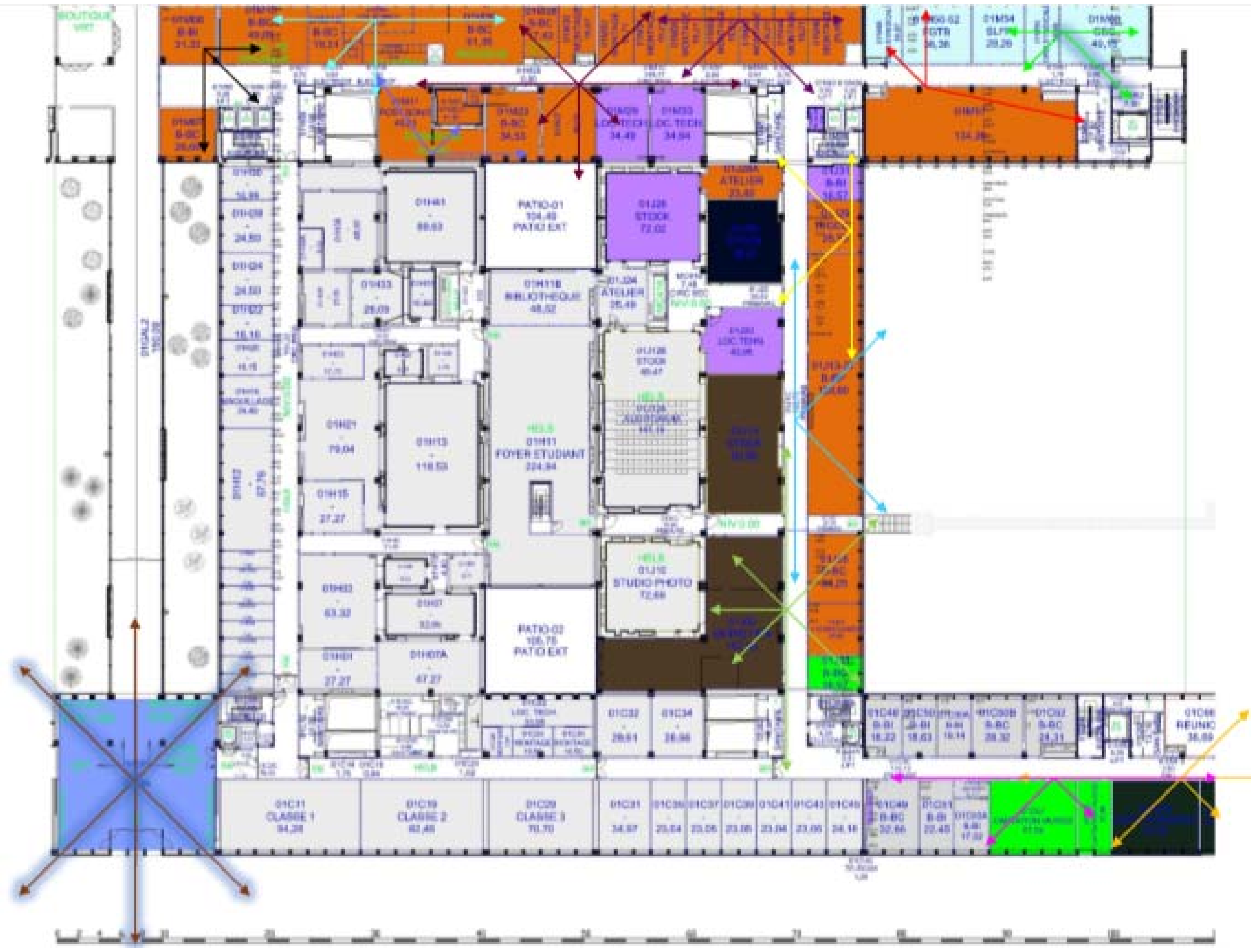

Figure 63 Design at 5 GHz for Floor 1 in Building PUVQ

❖ Ground Floor

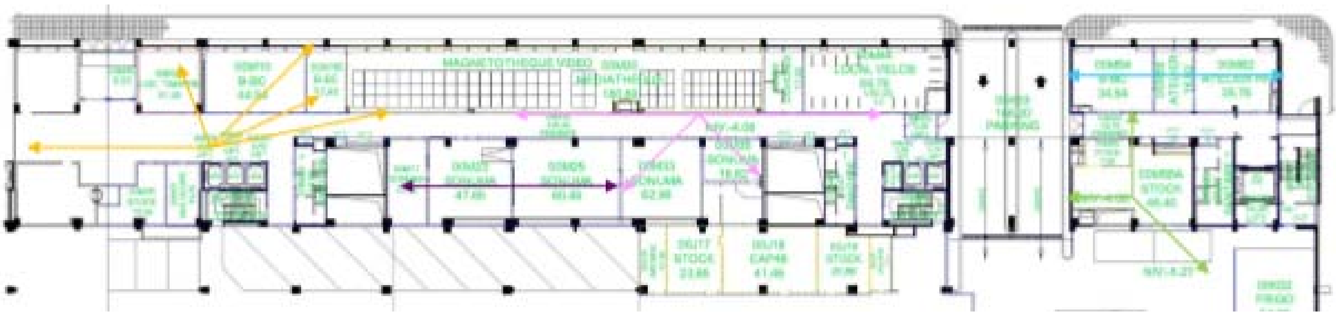

Figure 64 Design at 5 GHz for Ground Floor in Building PUVQ

10.2 Blueprints of the Actual Building at 2.4 GHz

The arrows represent the coverage of the APs in different and relevant direction. The center of the arrows reprensents the location of the APs.

- Building CHJM

❖ Eleventh Floor

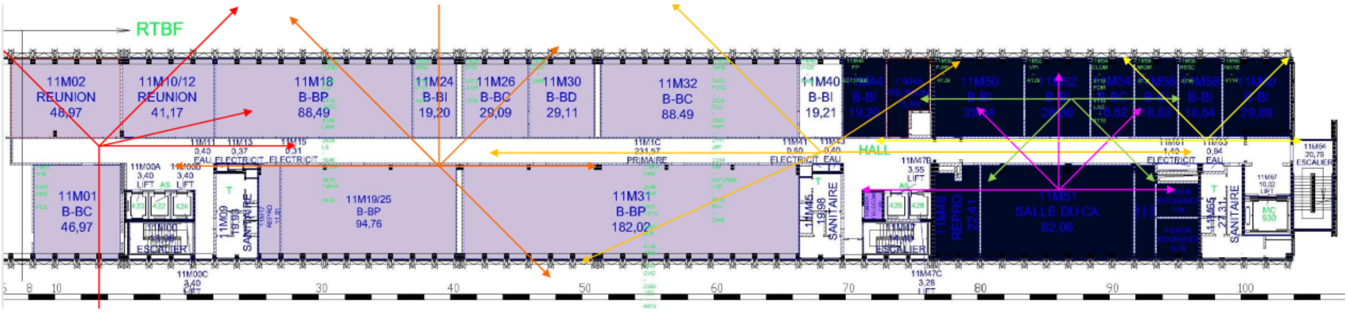

Figure 65 Design at 2.4 GHz for Floor 11 in Building CHJM

❖ Tenth Floor

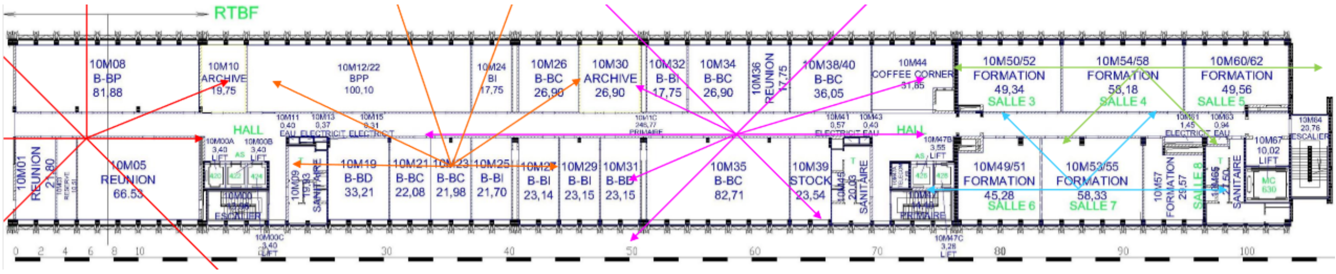

Figure 66 Design at 2.4 GHz for Floor 10 in Building CHJM

❖ Ninth Floor

Figure 67 Design at 2.4 GHz for Floor 9 in Building CHJM

- Eighth Floor

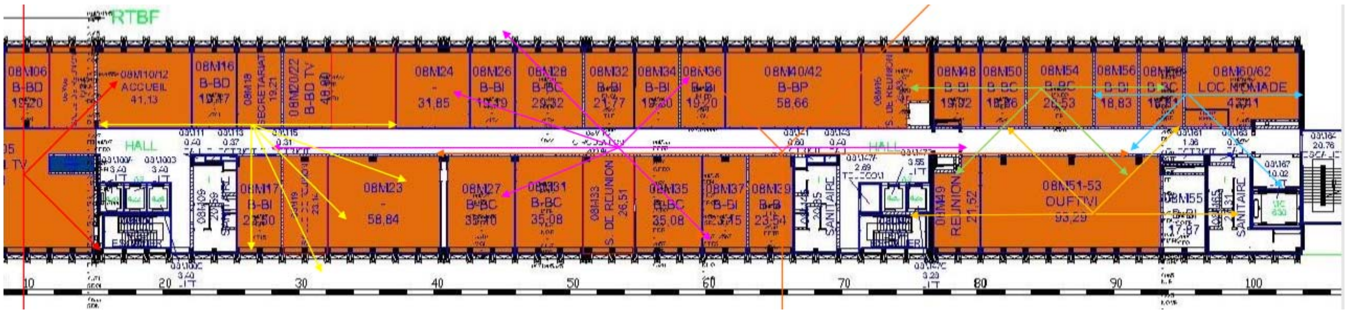

Figure 68 Design at 2.4 GHz for Floor 8 in Building CHJM

- Seventh Floor

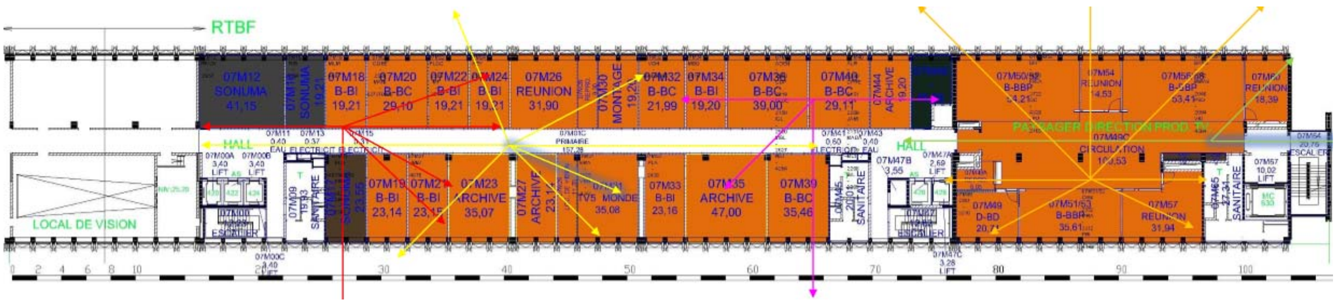

Figure 69 Design at 2.4 GHz for Floor 7 in Building CHJM

- Sixth Floor

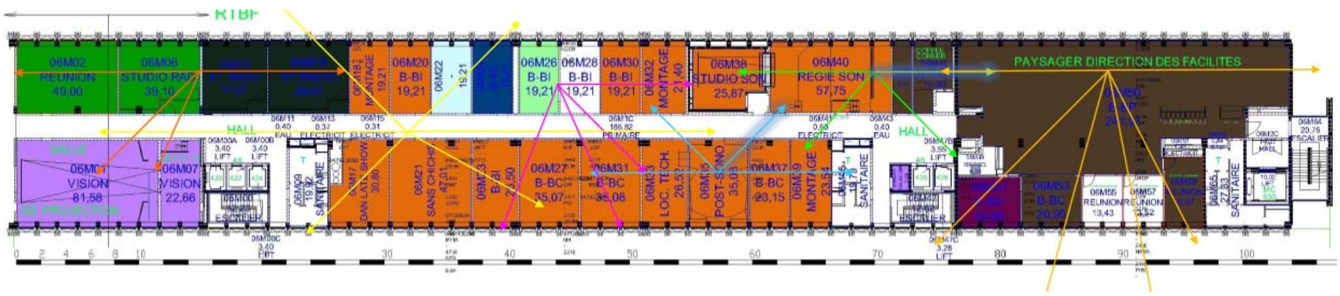

Figure 70 Design at 2.4 GHz for Floor 6 in Building CHJM

- Fifth Floor

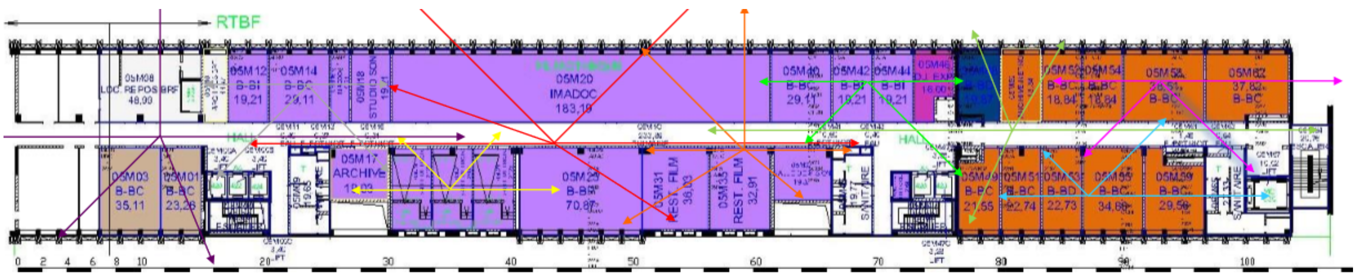

Figure 71 Design at 2.4 GHz for Floor 5 in Building CHJM

❖ Fourth Floor

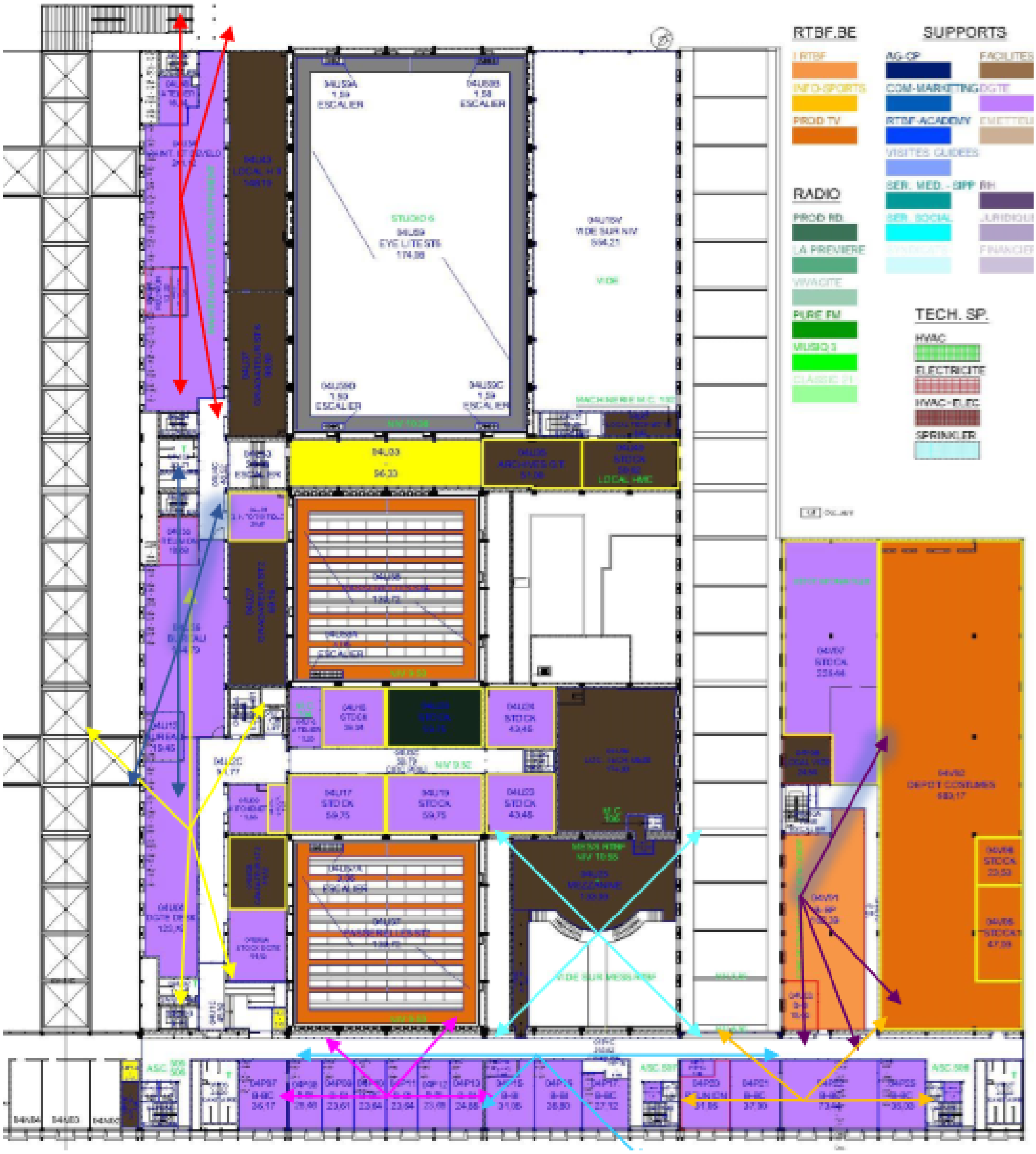

Figure 72 Design at 2.4 GHz for Floor 2 in Building CHJM

❖ Third Floor

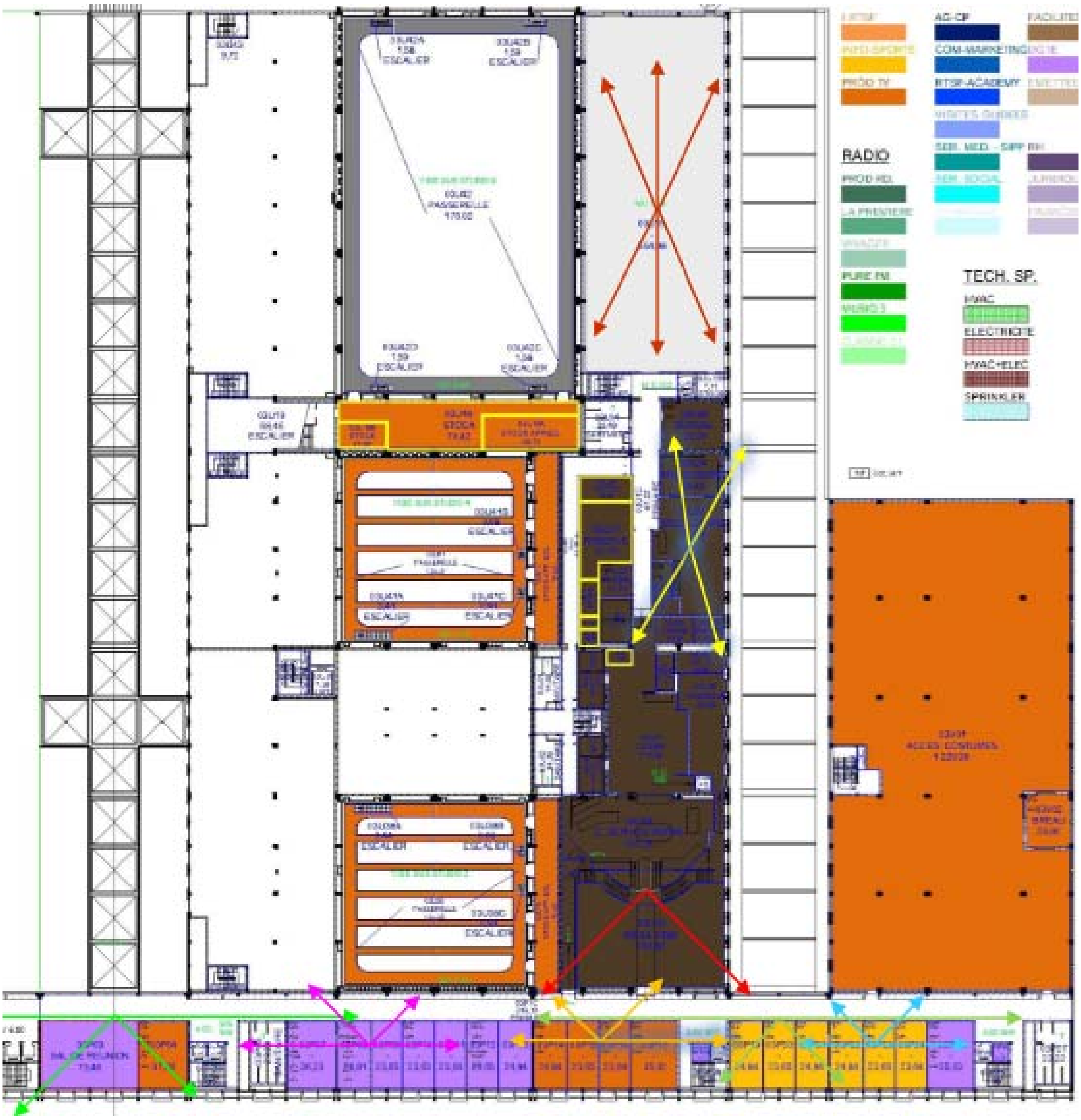

Figure 73 Design at 2.4 GHz for Floor 3 in Building CHJM

- Second Floor

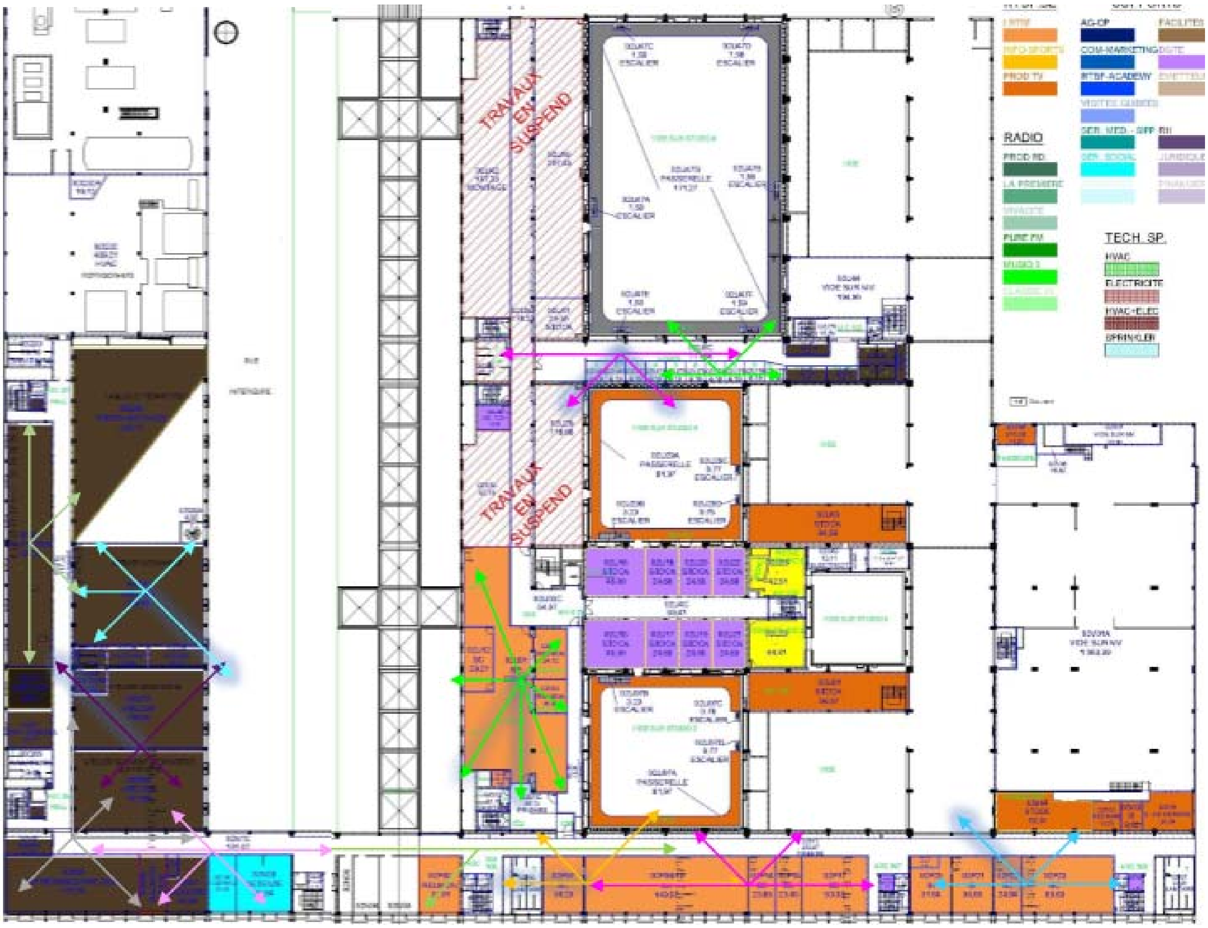

Figure 74 Design at 2.4 GHz for Floor 2 in Building CHJM

❖ First Floor

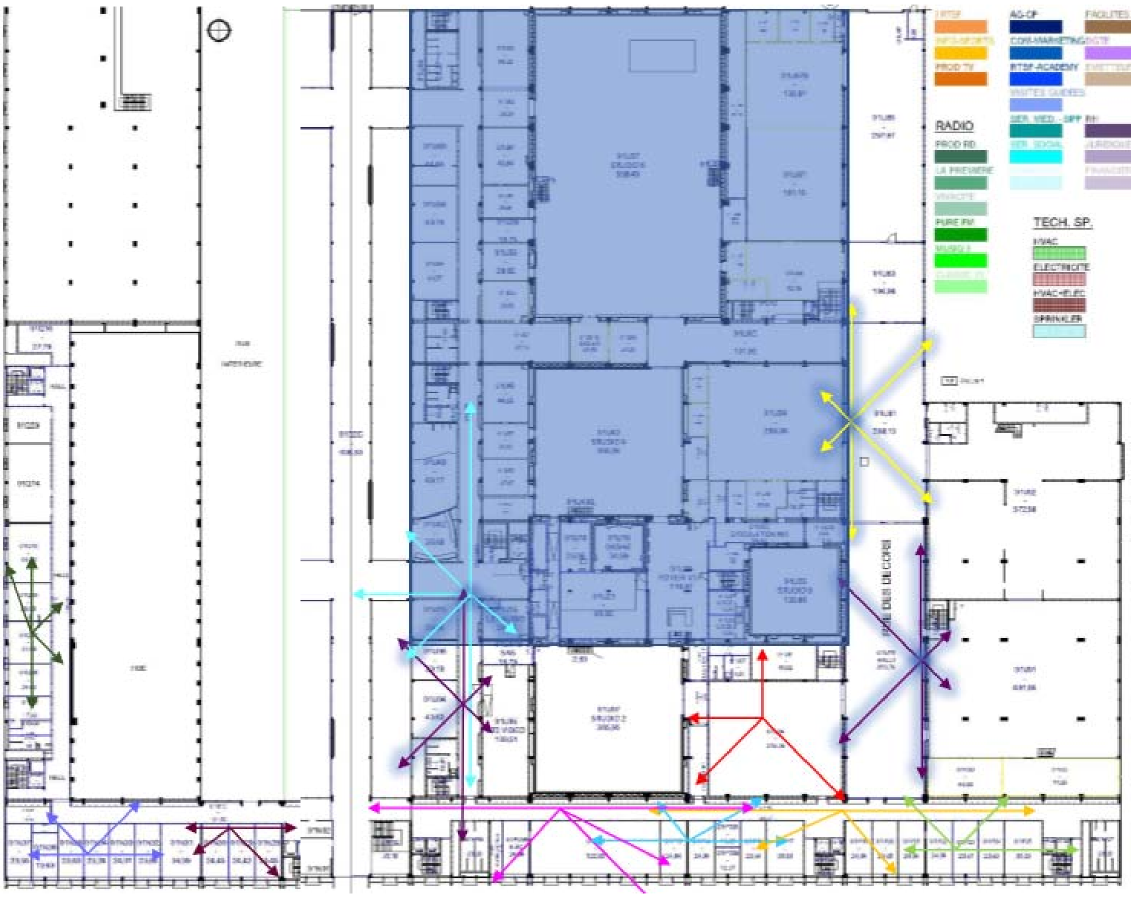

Figure 75 Design at 2.4 GHz for Floor 1 in Building CHJM

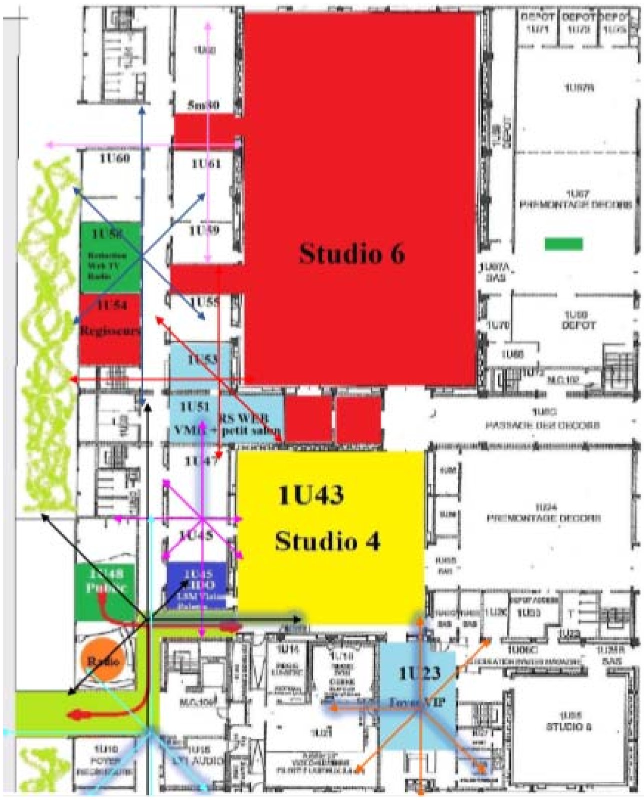

Figure 76 Design at 2.4 GHz for Floor 1 Television Studio in Building CHJM

- Ground Floor

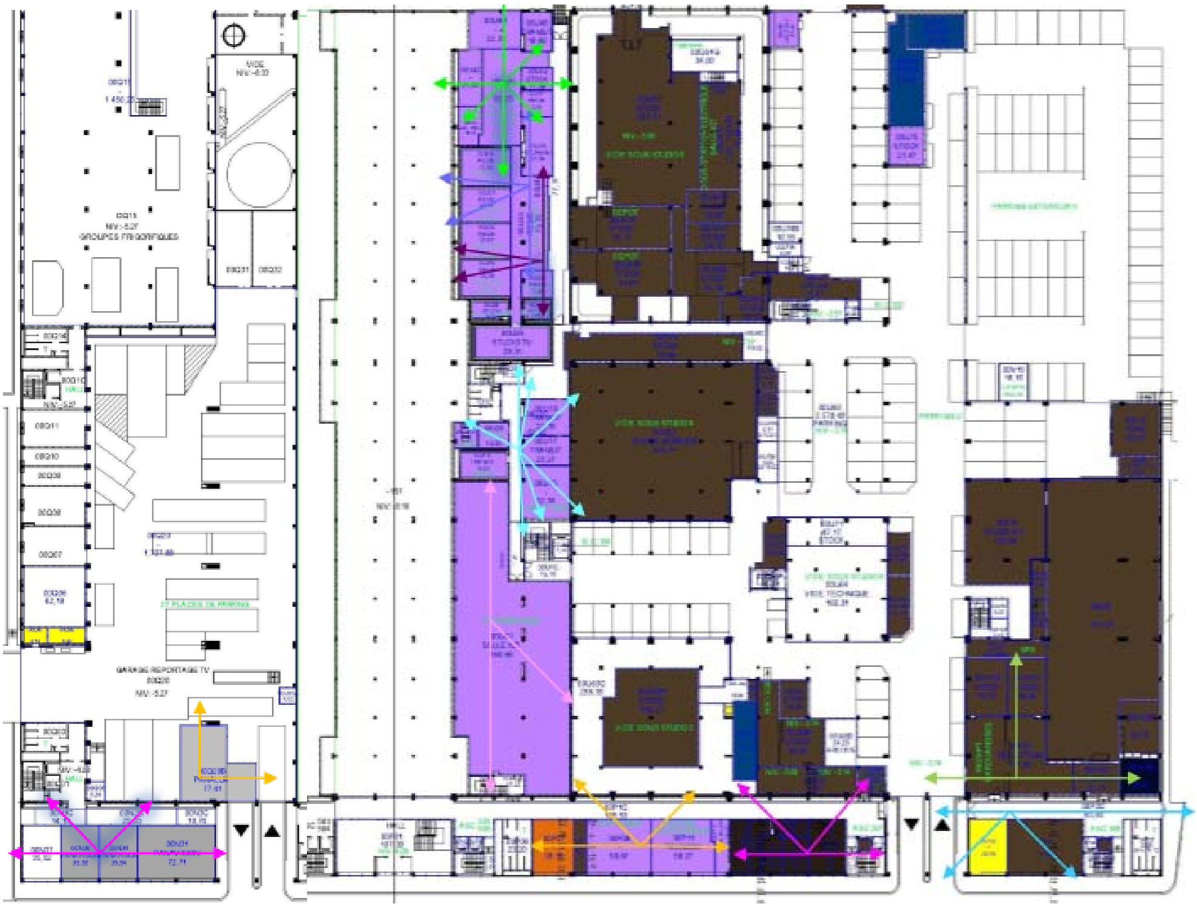

Figure 77 Design at 2.4 GHz for Ground Floor in Building CHJM

- Building PUVQ

❖ Fourth Floor

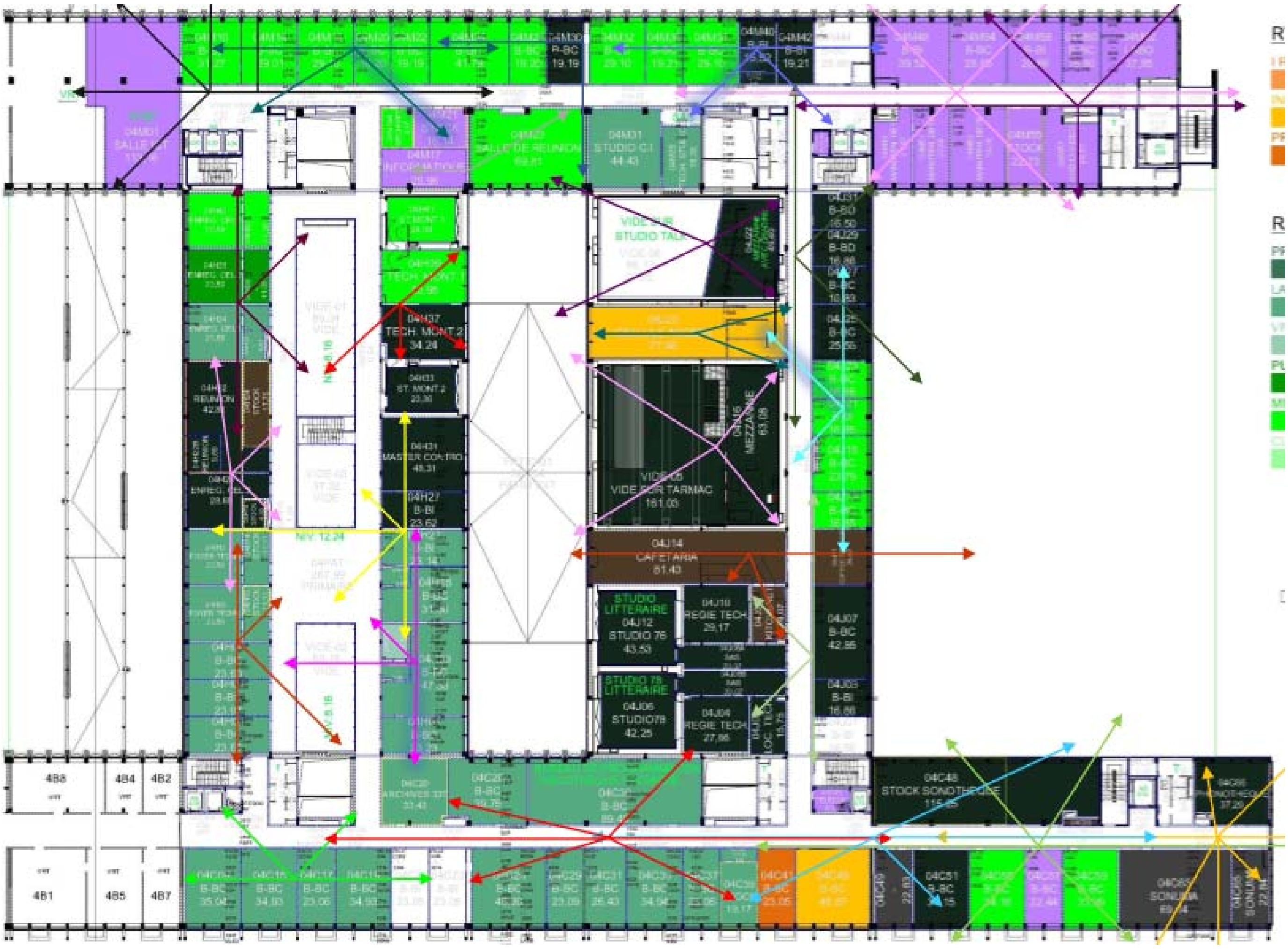

Figure 78 Design at 2.4 GHz for Floor 4 in Building PUVQ

❖ Third Floor

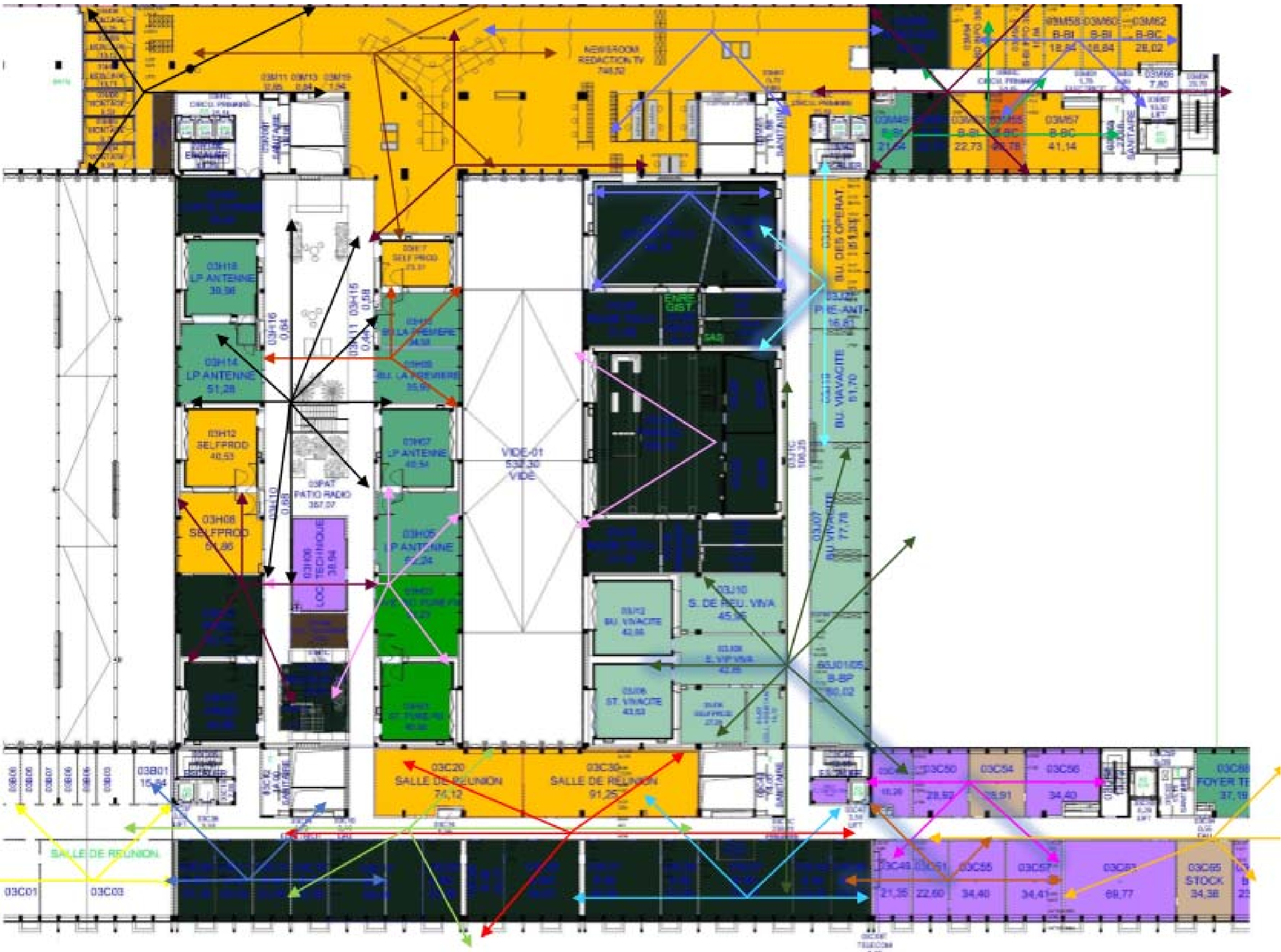

Figure 79 Design at 2.4 GHz for Floor 3 in Building PUVQ

❖ Second Floor

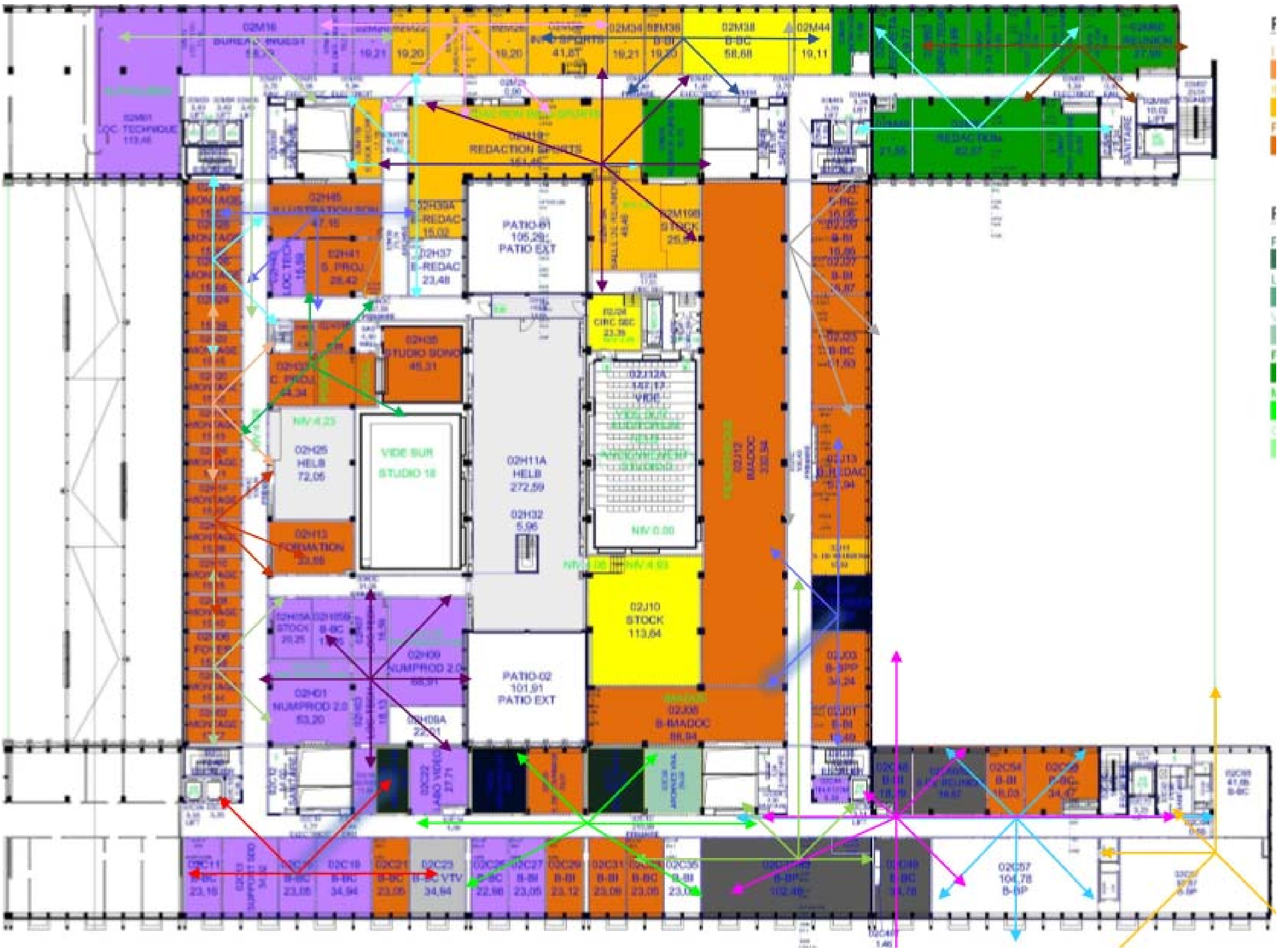

Figure 80 Design at 2.4 GHz for Floor 2 in Building PUVQ

❖ First Floor

Figure 81 Design at 2.4 GHz for Floor 1 in Building PUVQ

❖ Ground Floor

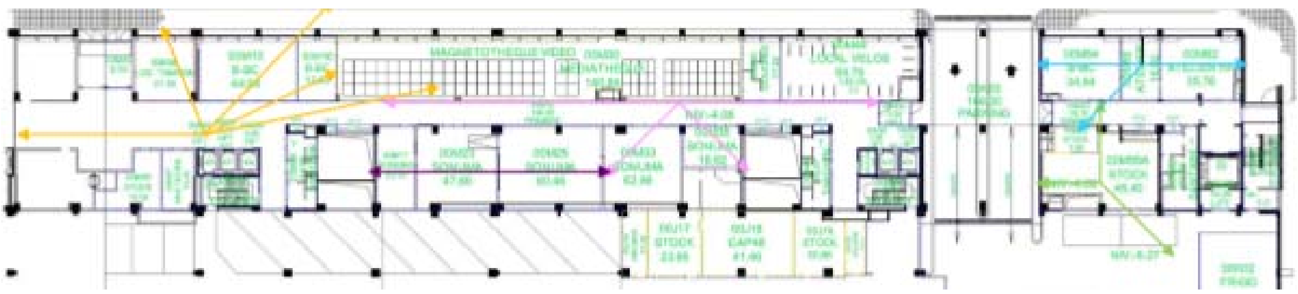

Figure 82 Design at 2.4 GHz for Ground Floor in Building PUVQ

10.3 Blueprints of the Future Building at 5 GHz – Worst Case

The circles refer to the APs coverage and the center of those circle are the APs locations. The main levels are represented by two maps, indicating the different material attenuation by circles differing by size and color.

- Parking Level -2

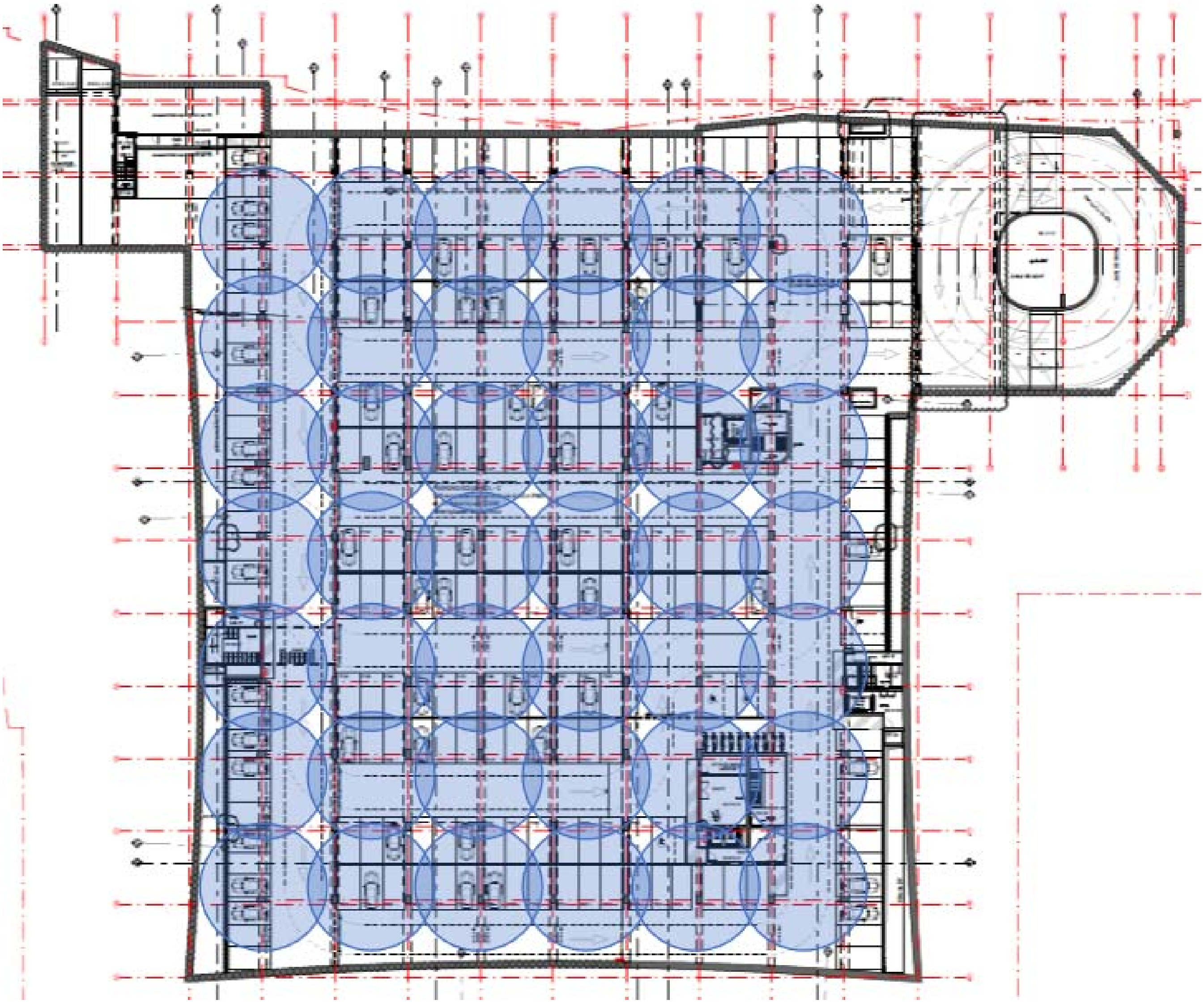

Figure 83 Coverage Access Points for Parking Level -2 in the Worst Case

- Parking Level -1

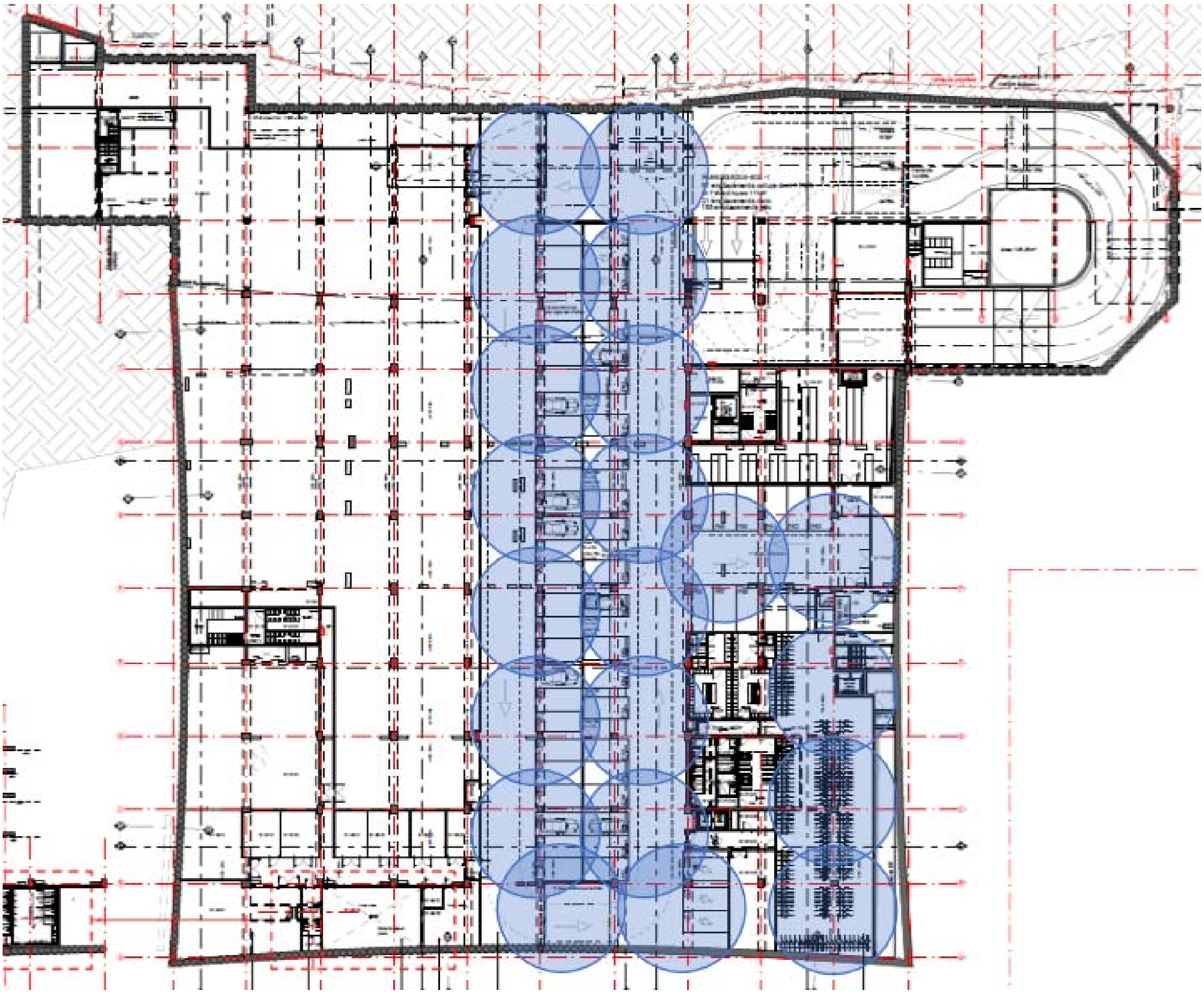

Figure 84 Coverage Access Points for Parking Level -1 in the Worst Case

- Ground Floor

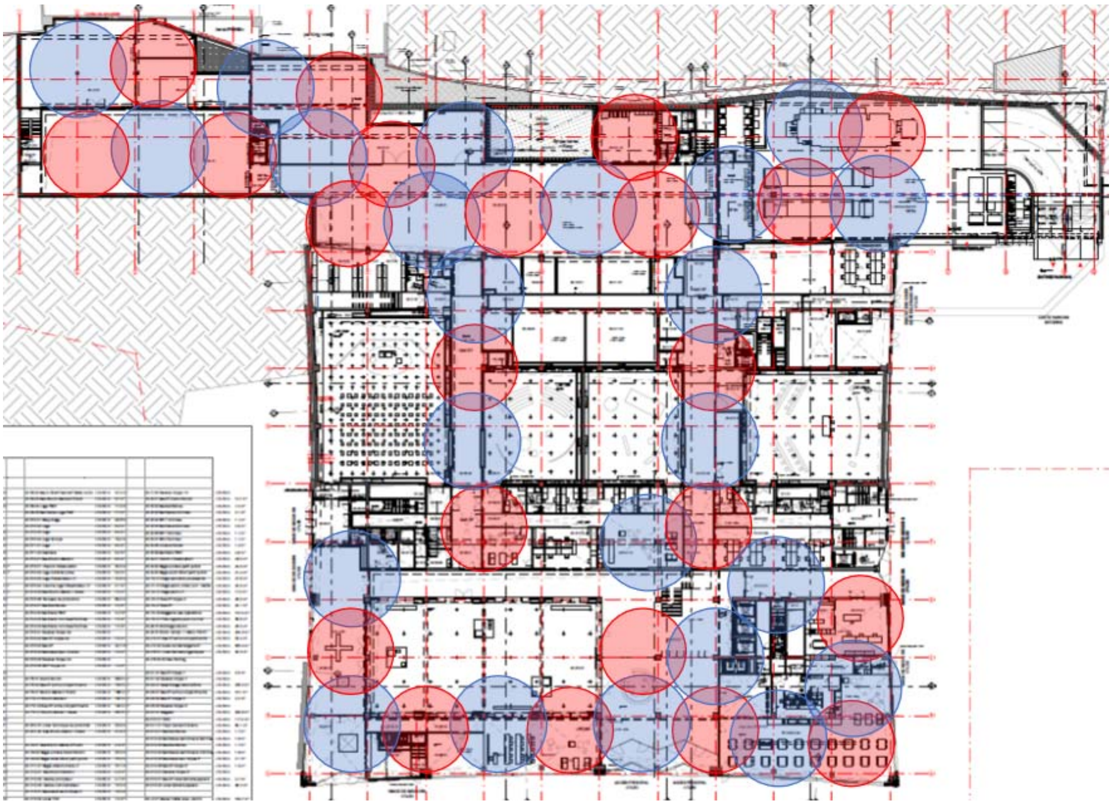

Figure 85 Coverage Access Points for Ground Floor in the Worst Case

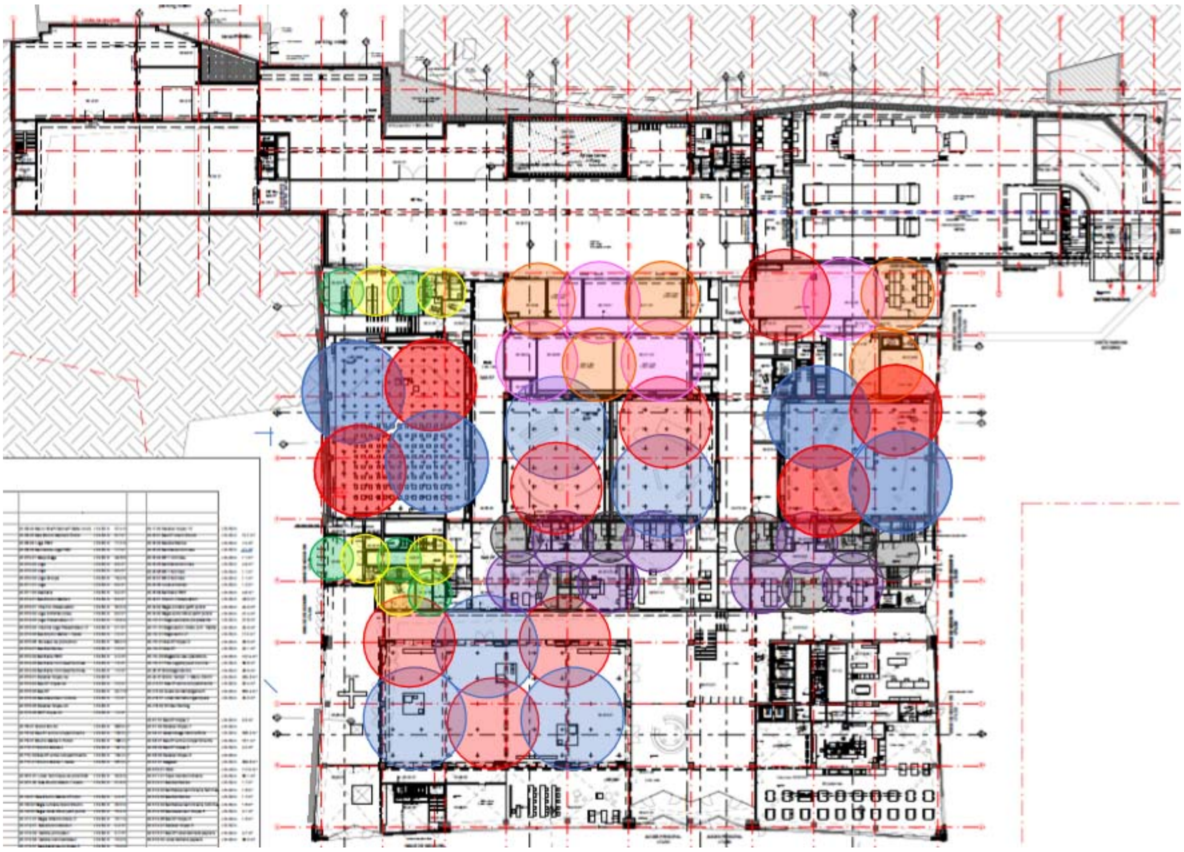

Figure 86 Coverage Access Points for Floor 1 in the Worst Case

❖ First Floor

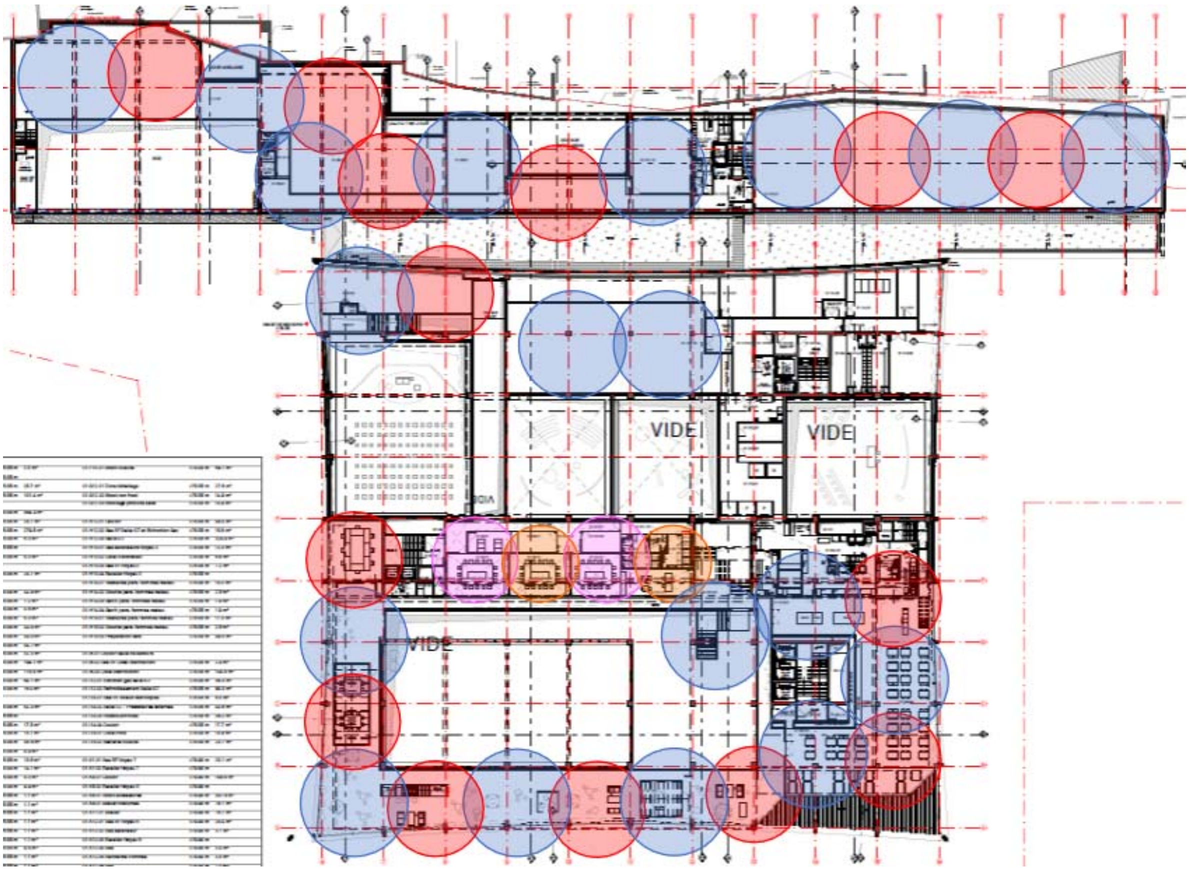

Figure 87 Coverage Access Points for Floor 2 in the Worst Case

Figure 88 Coverage Access Points for Floor 1 in the Worst Case

❖ Second Floor

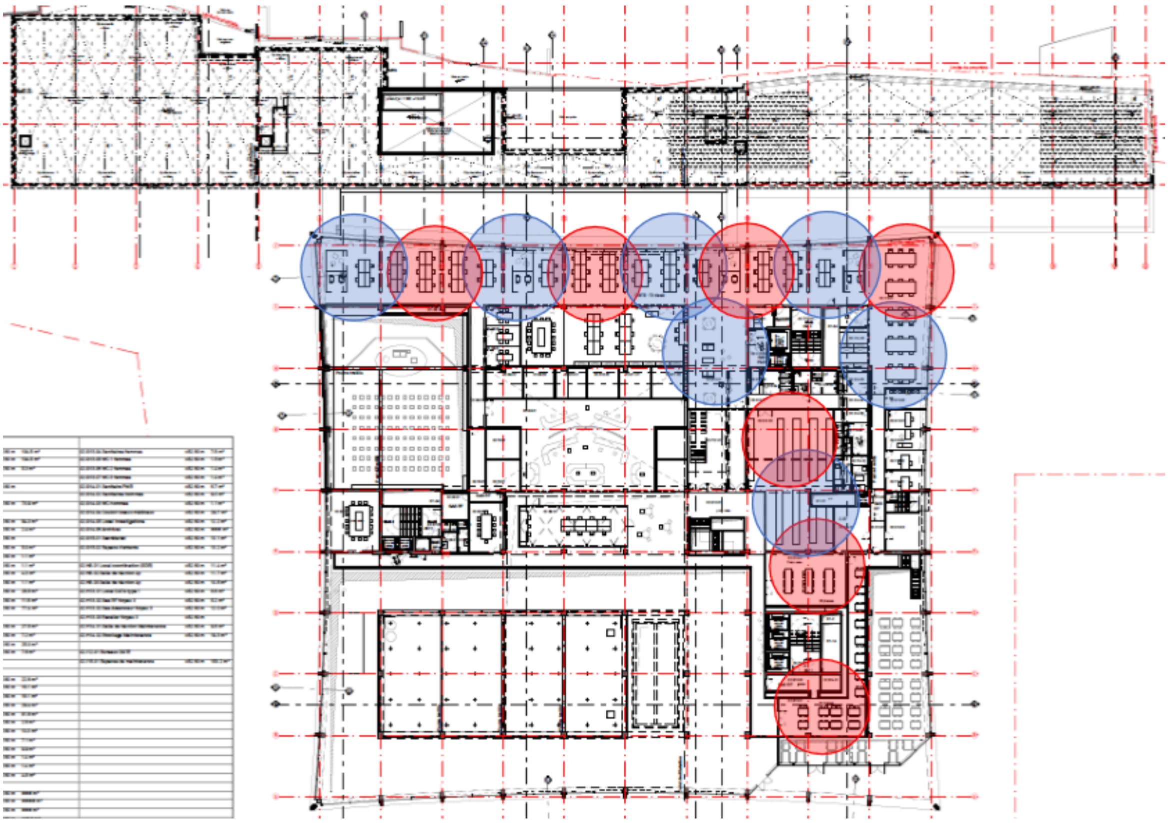

Figure 89 Coverage Access Points for Floor 2 in the Worst Case

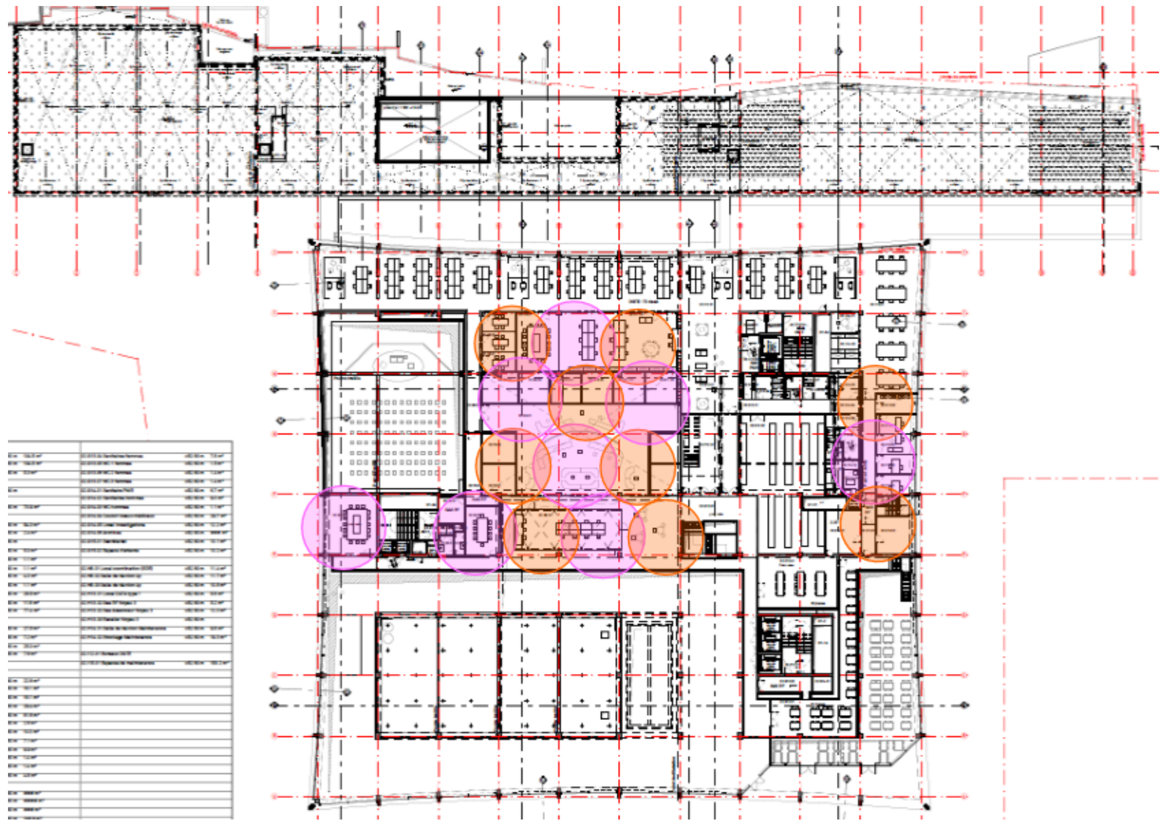

Figure 90 Coverage Access Points for Floor 2 in the Worst Case

- Third Floor

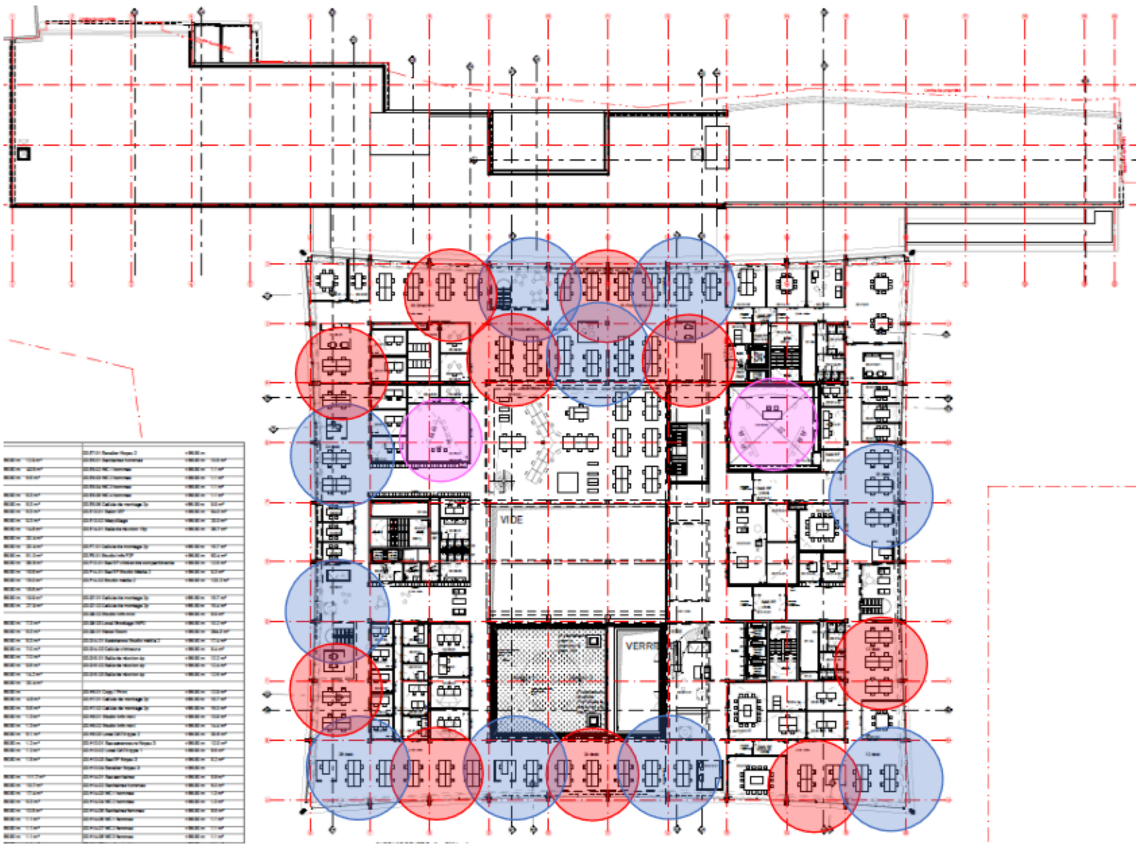

Figure 91 Coverage Access Points for Floor 3 in the Worst Case

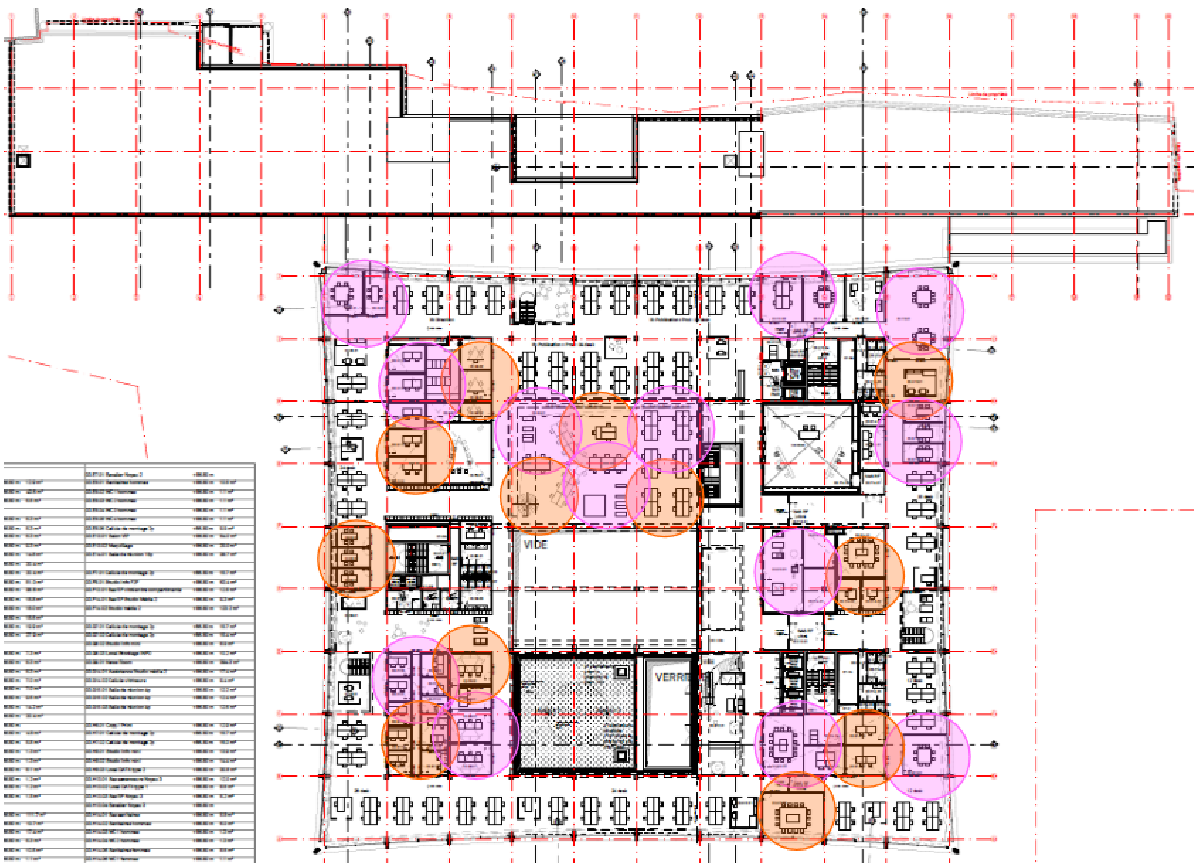

Figure 92 Coverage Access Points for Floor 3 in the Worst Case

❖ Fourth Floor

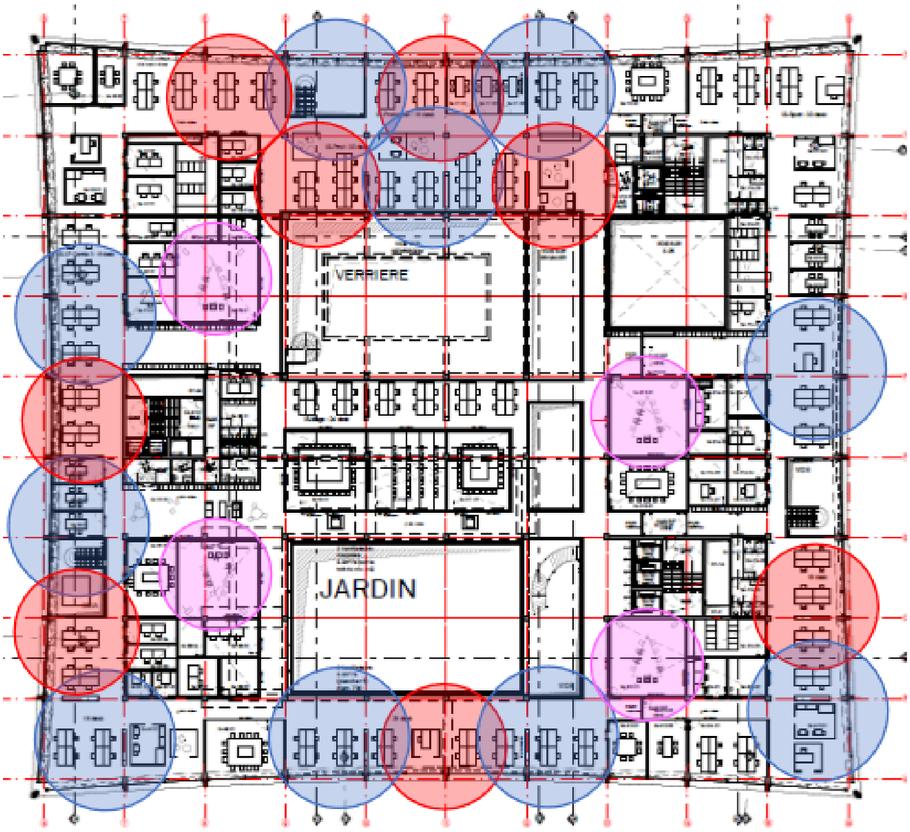

Figure 93 Coverage Access Points for Floor 4 in the Worst Case

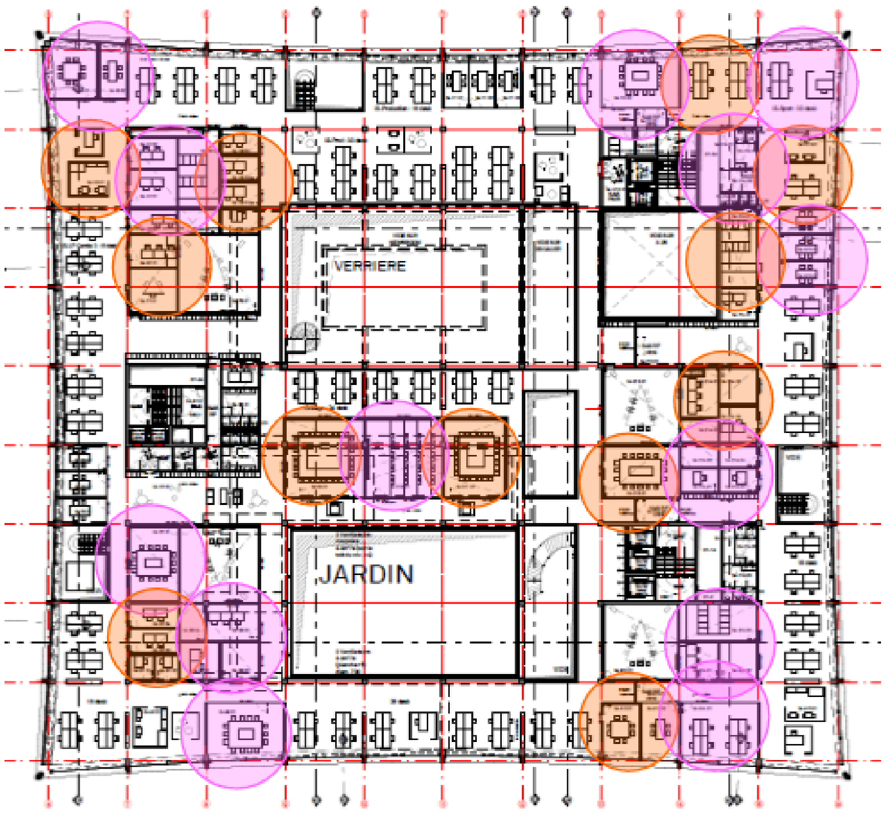

Figure 94 Coverage Access Points for Floor 4 in the Worst Case

❖ Fifth Floor

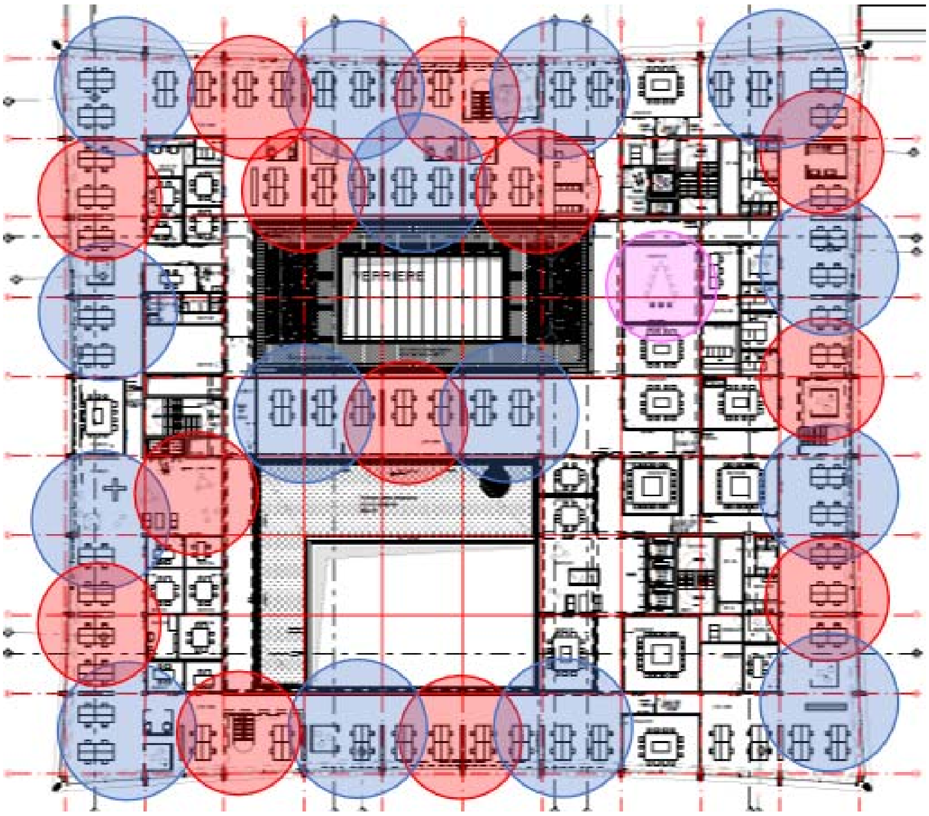

Figure 95 Coverage Access Points for Floor 5 in the Worst Case

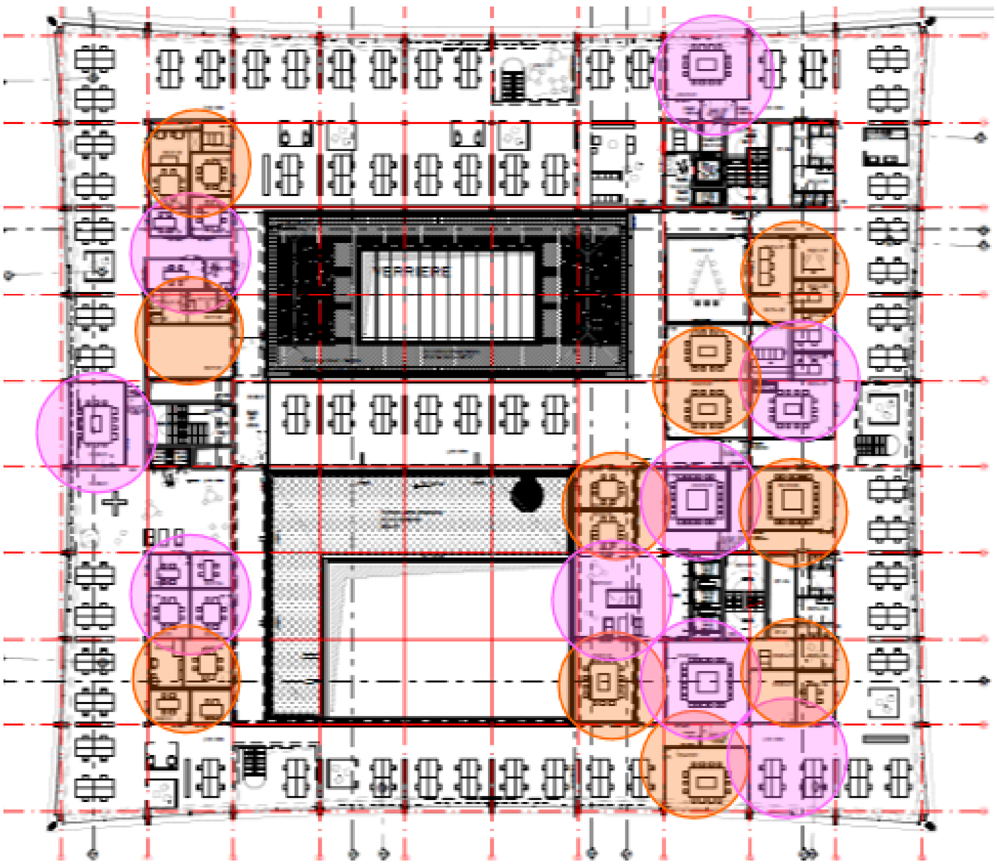

Figure 96 Coverage Access Points for Floor 5 in the Worst Case

❖ Sixth Floor

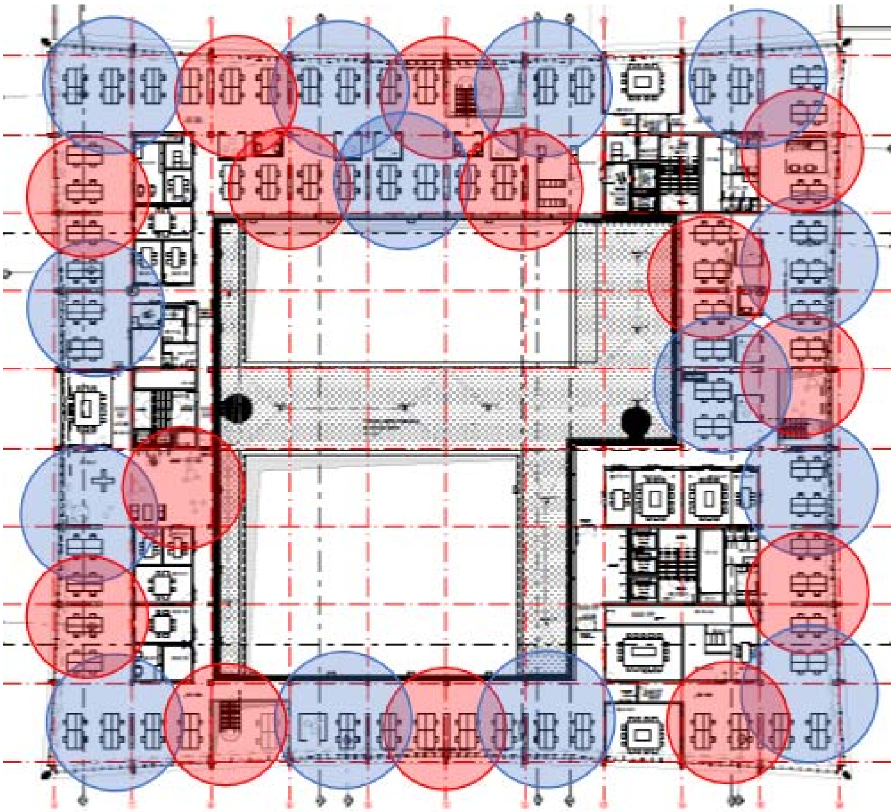

Figure 97 Coverage Access Points for Floor 6 in the Worst Case

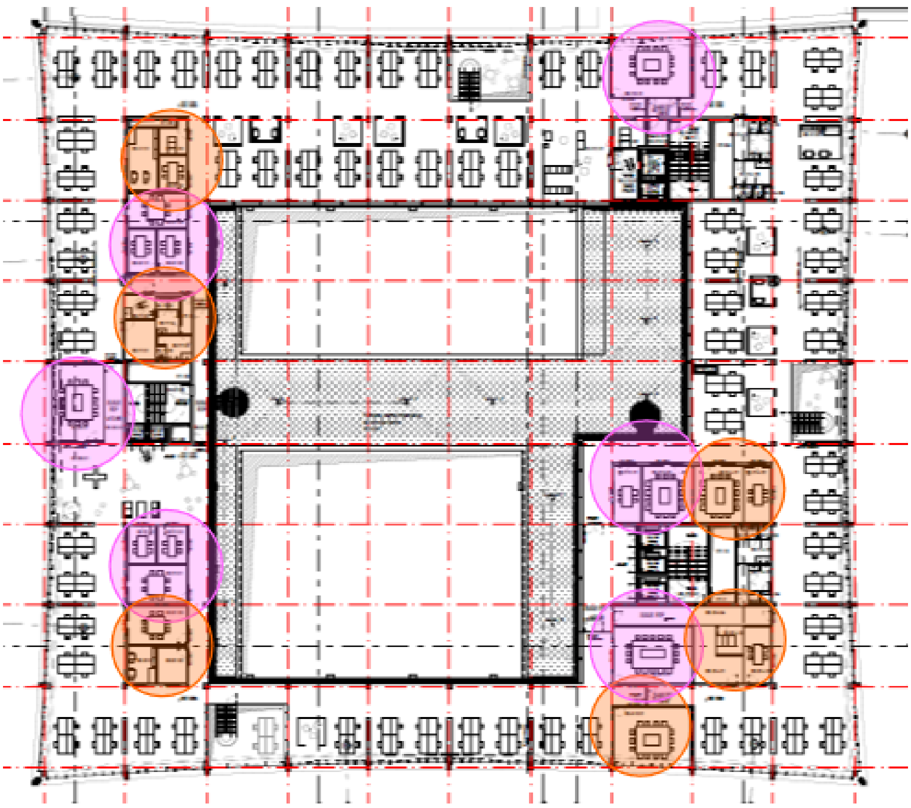

Figure 98 Coverage Access Points for Floor 6 in the Worst Case

10.4 Blueprints of the Actual Building at 5 GHz – Best Case

The circles refer to the APs coverage and the center of those circle are the APs locations. The main levels are represented by two maps, indicating the different material attenuation by circles differing by size and color.

- Parking Floor -2

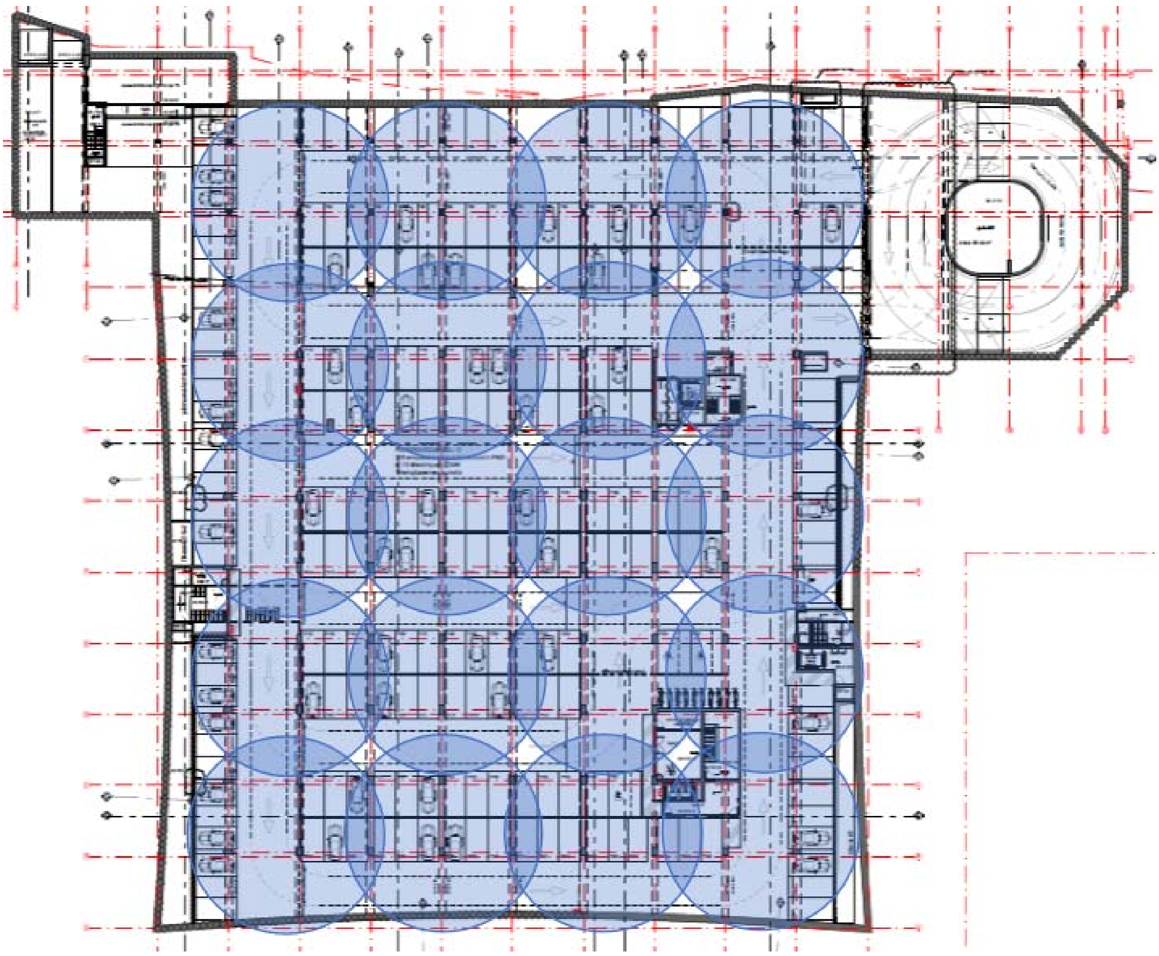

Figure 99 Coverage Access Points for Parking Level -2 in the Best Case

❖ Parking Floor -1

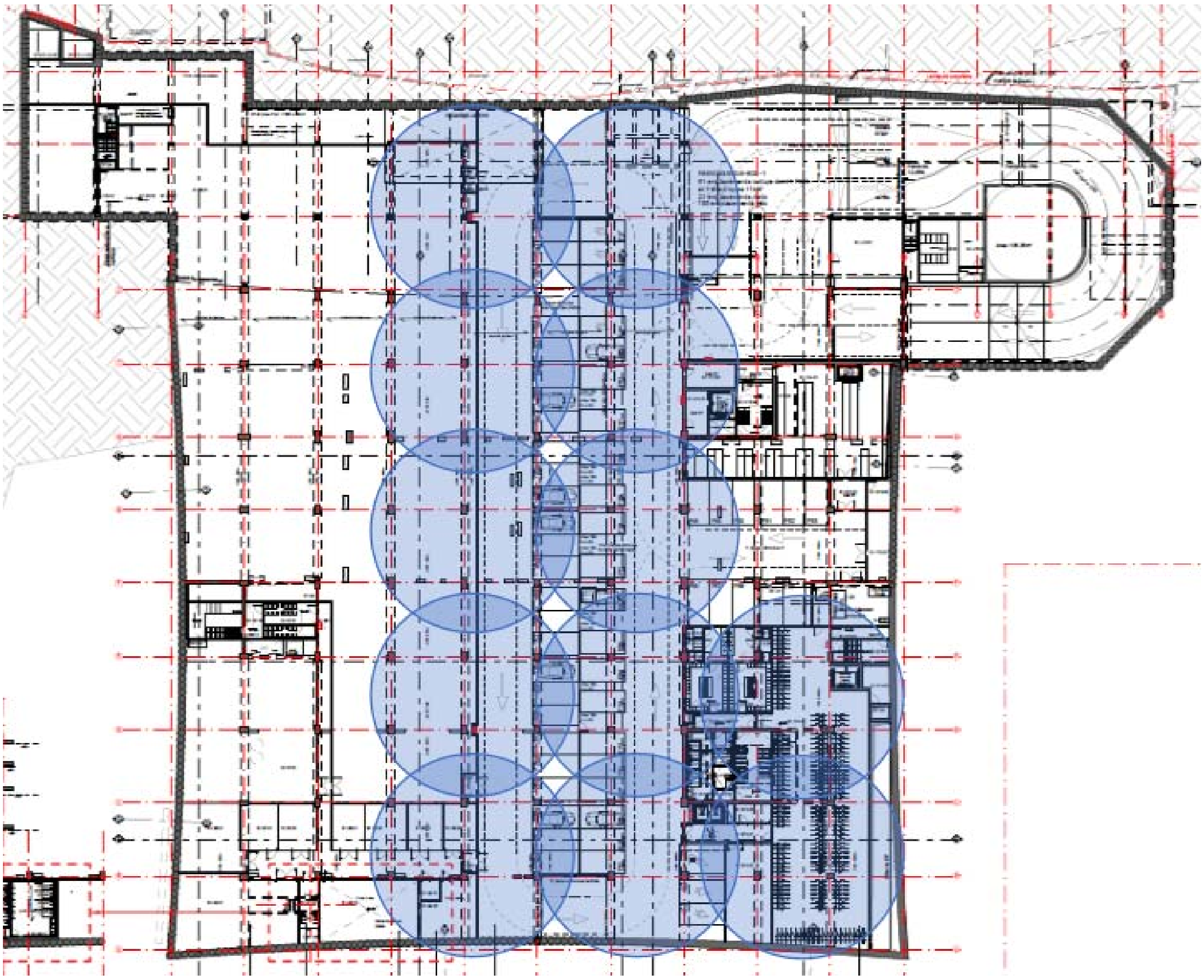
Figure 100 Coverage Access Points for Parking Level -1 in the Best Case

❖ Ground Floor

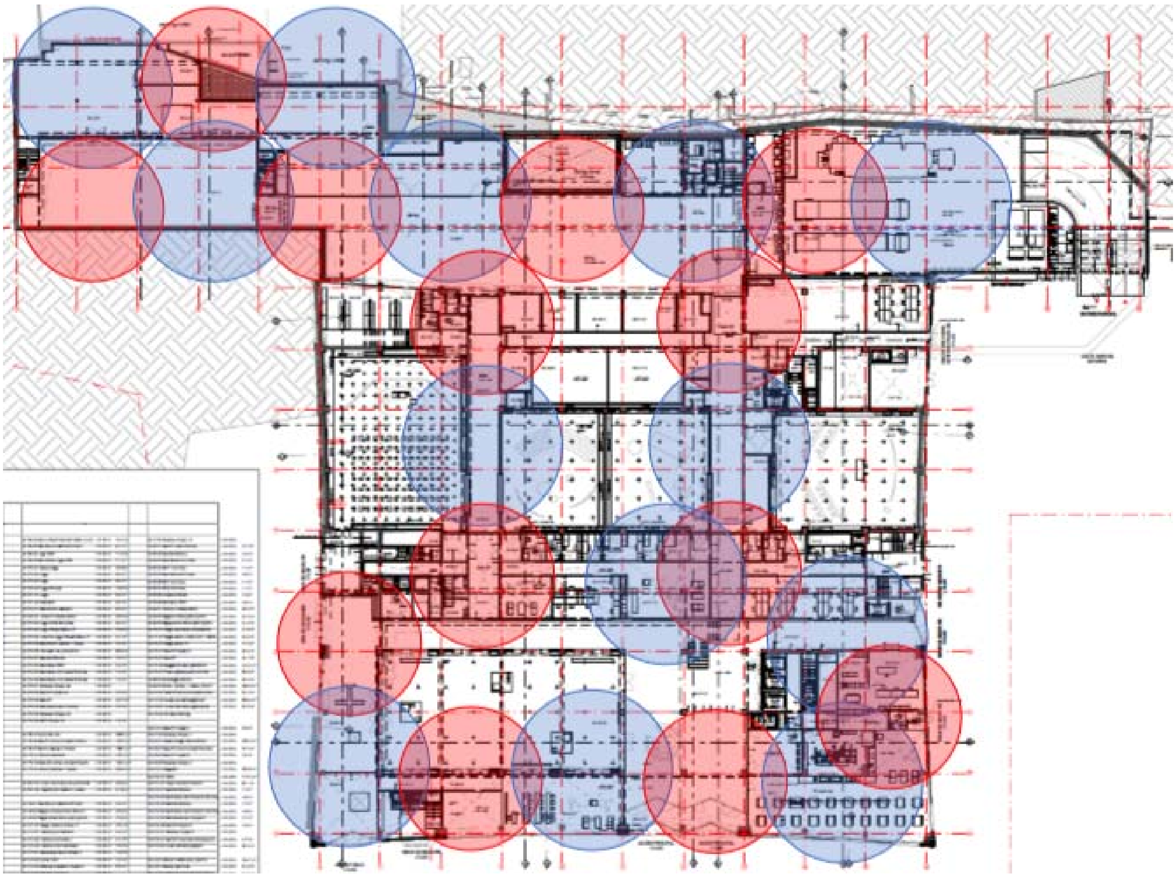

Figure 101 Coverage Access Points for Ground Floor in the Best Case

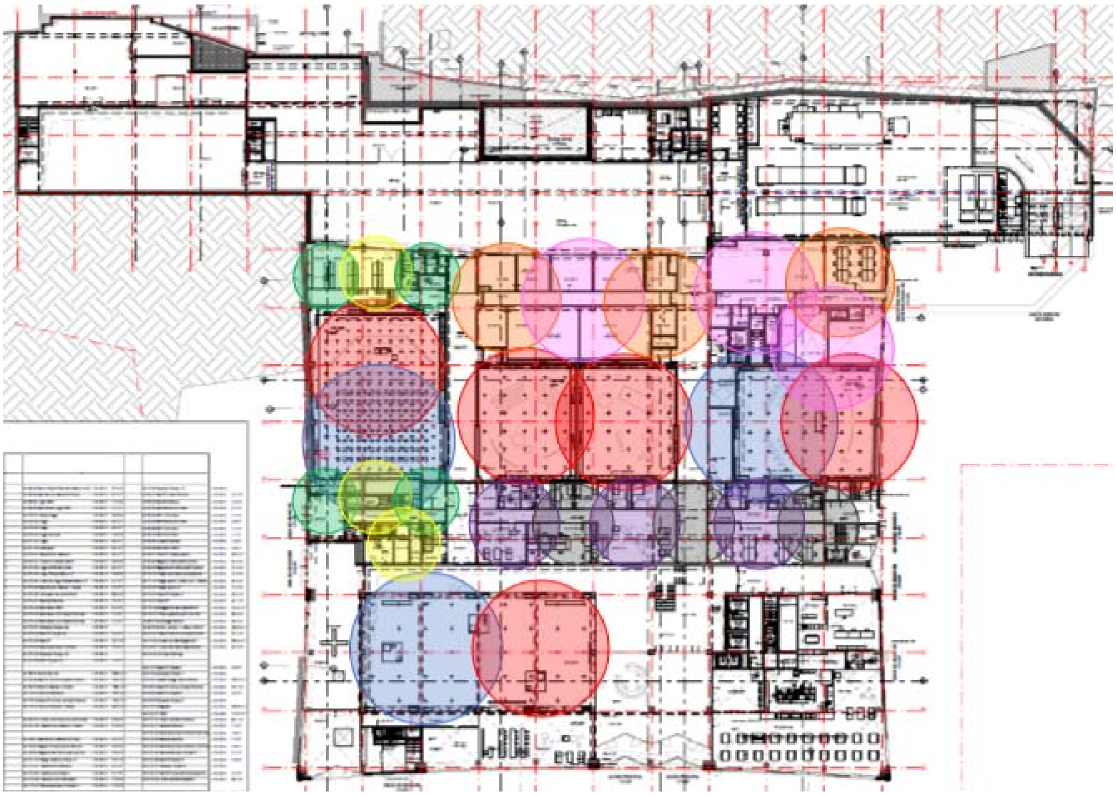

Figure 102 Coverage Access Points for Ground Floor in the Best Case

- First Floor

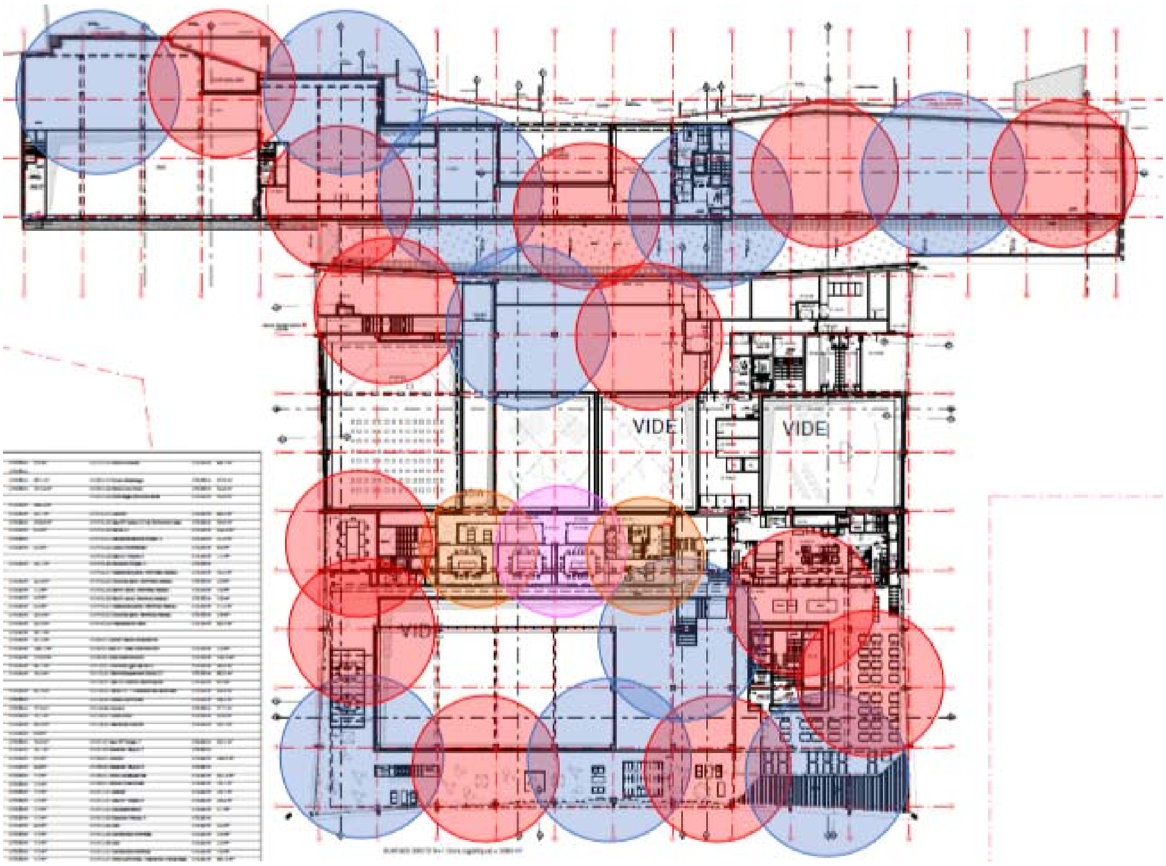

Figure 103 Coverage Access Points for Floor 1 in the Best Case

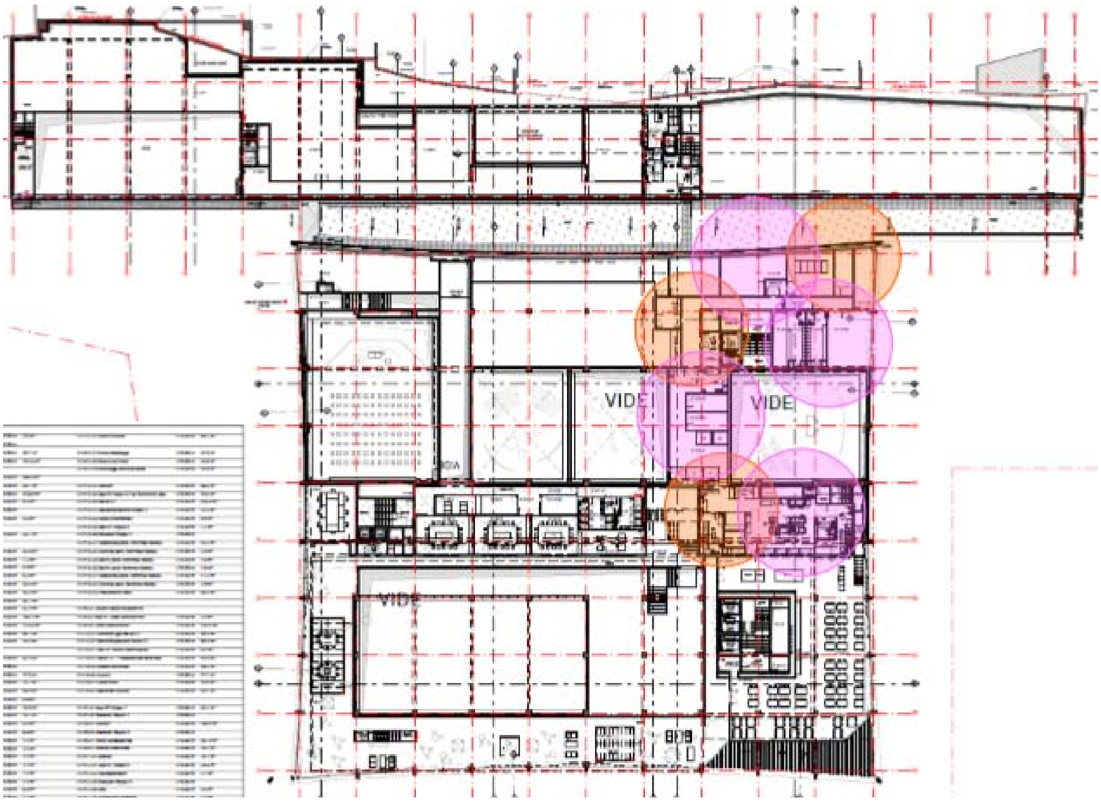

Figure 104 Coverage Access Points for Floor 1 in the Best Case

❖ Second Floor

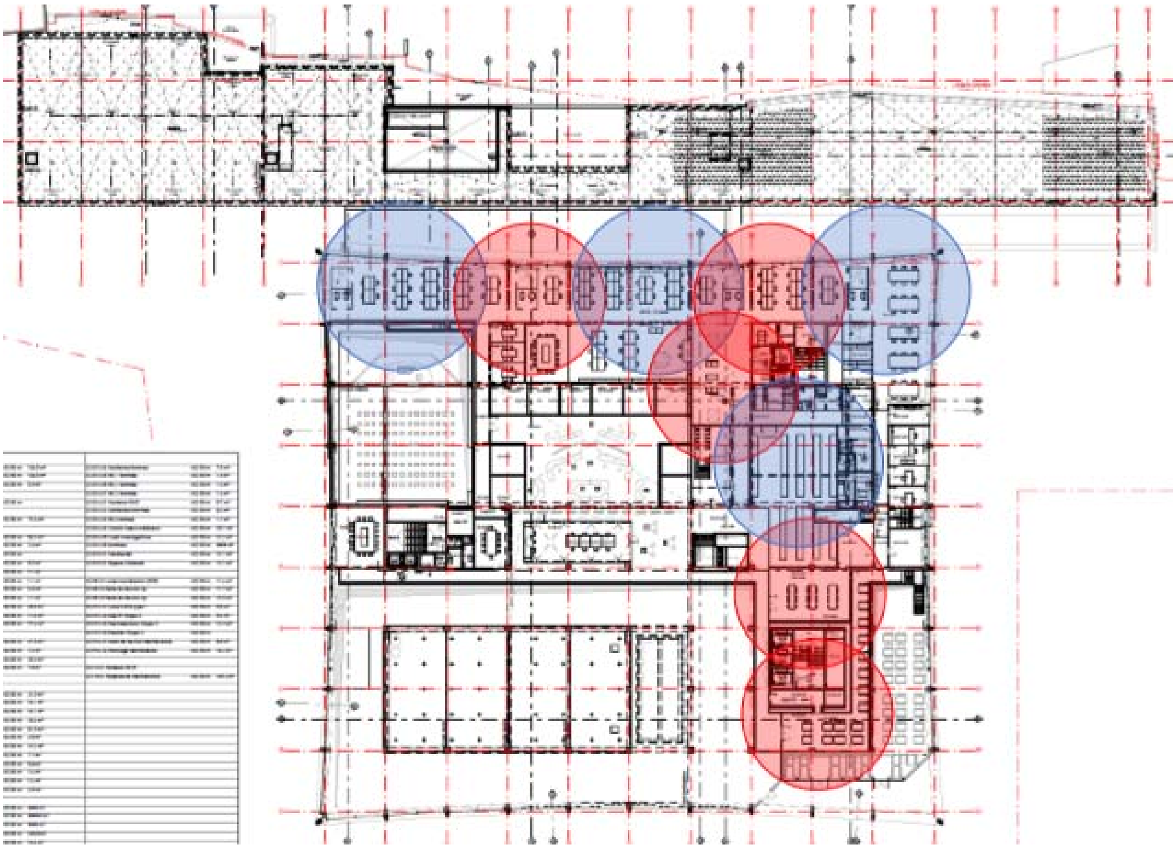

Figure 105 Coverage Access Points for Floor 2 in the Best Case

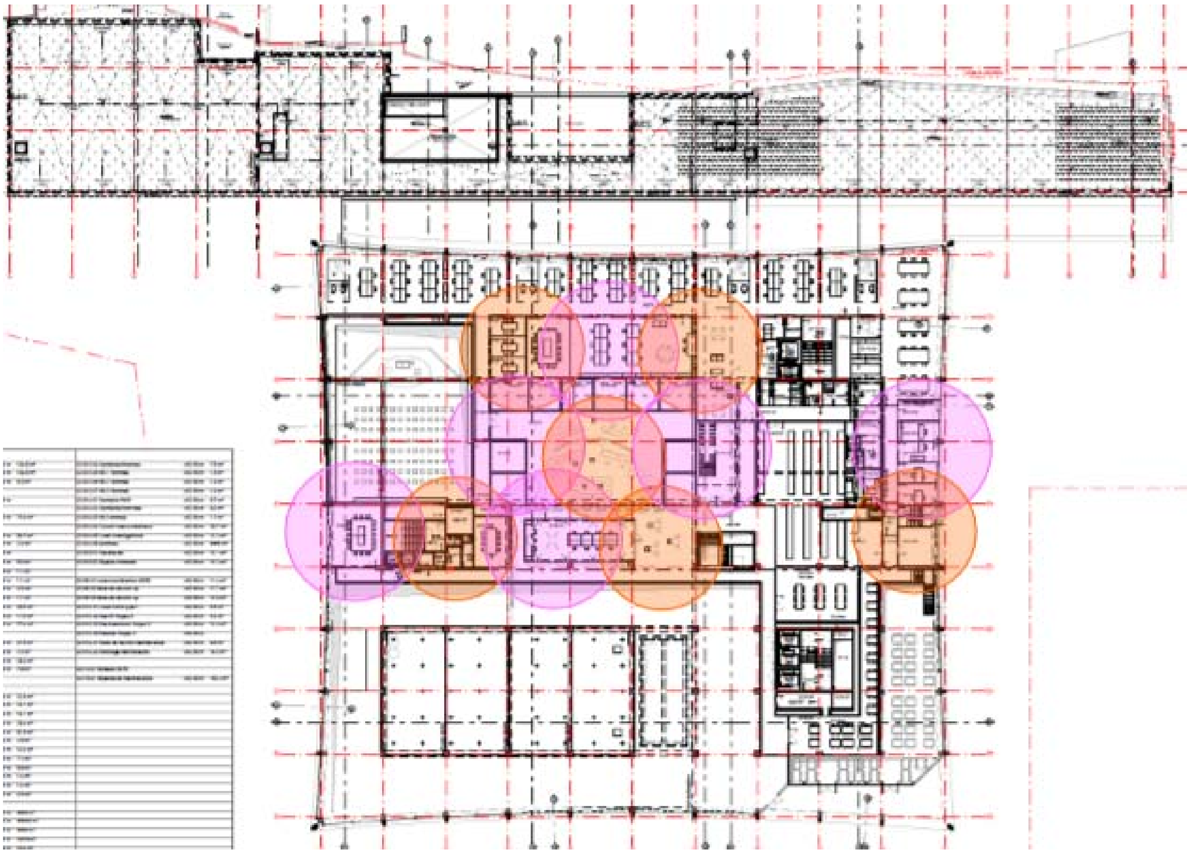

Figure 106 Coverage Access Points for Floor 2 in the Best Case

❖ Thirth Floor

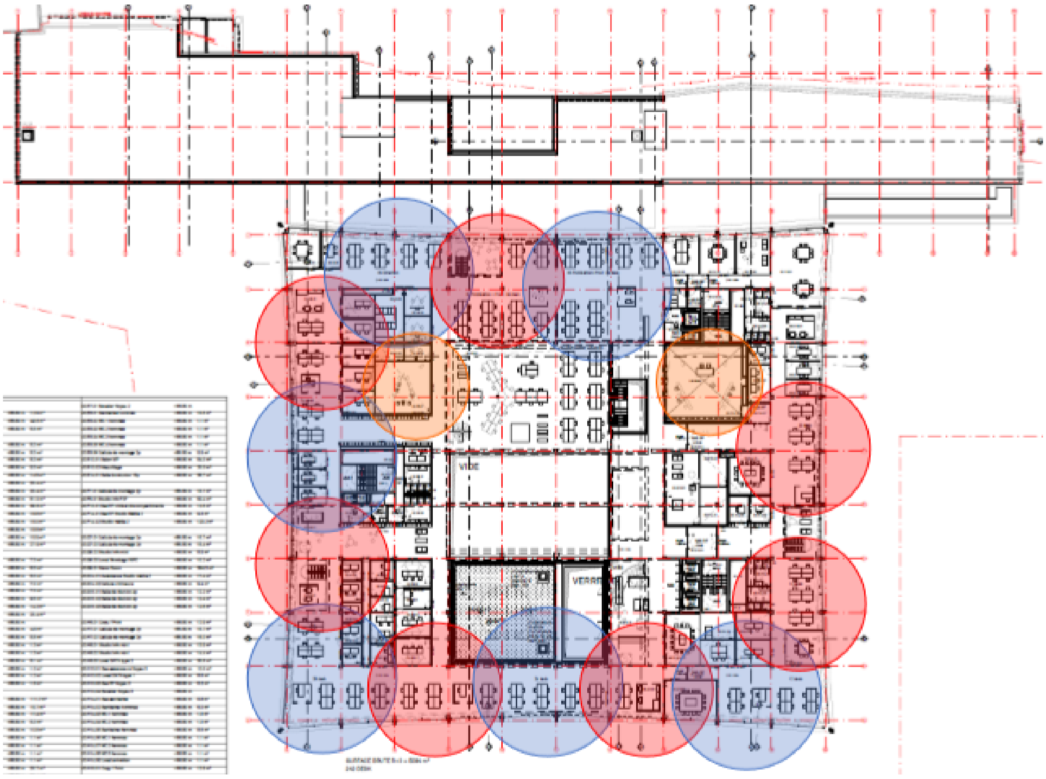

Figure 107 Coverage Access Points for Floor 3 in the Best Case

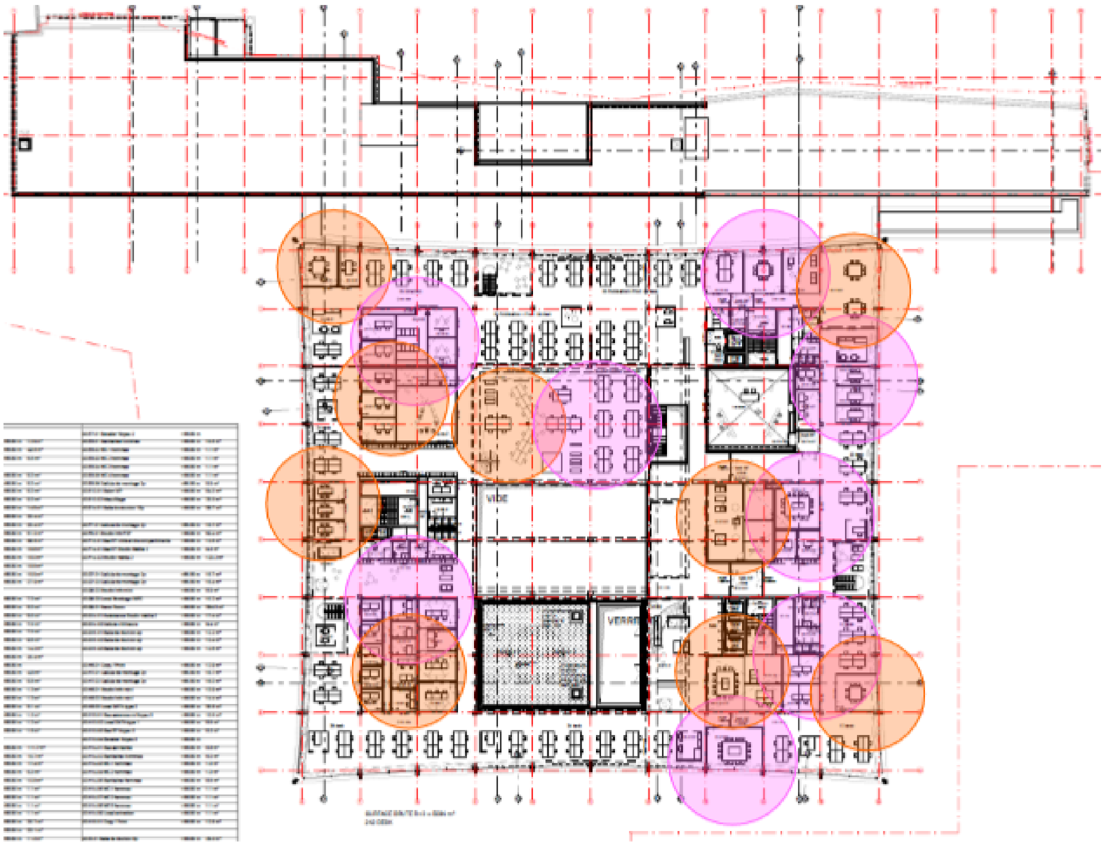

Figure 108 Coverage Access Points for Floor 3 in the Best Case

❖ Fourth Floor

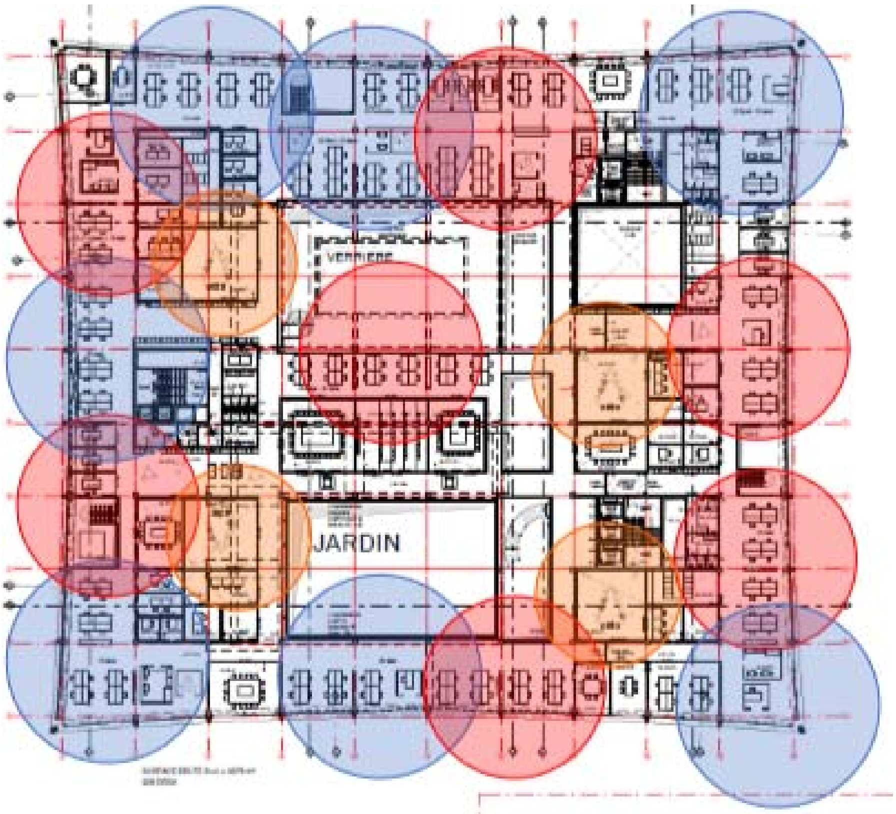

Figure 109 Coverage Access Points for Floor 4 in the Best Case

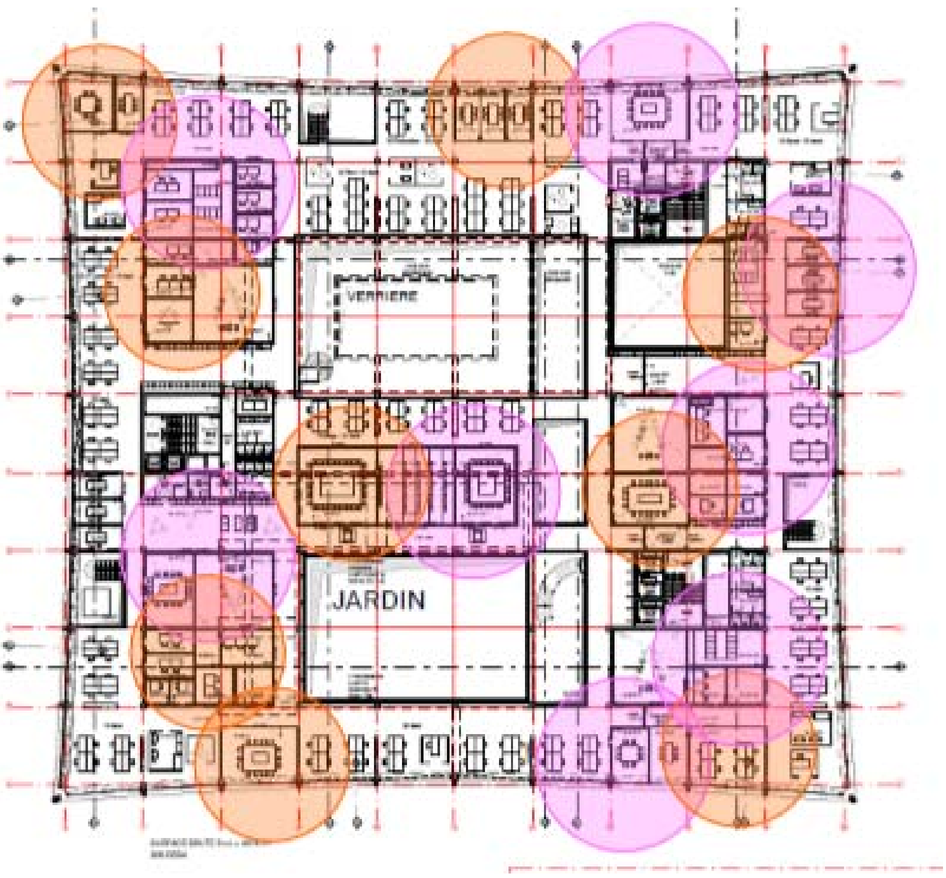

Figure 110 Coverage Access Points for Floor 4 in the Best Case

- Fifth Floor

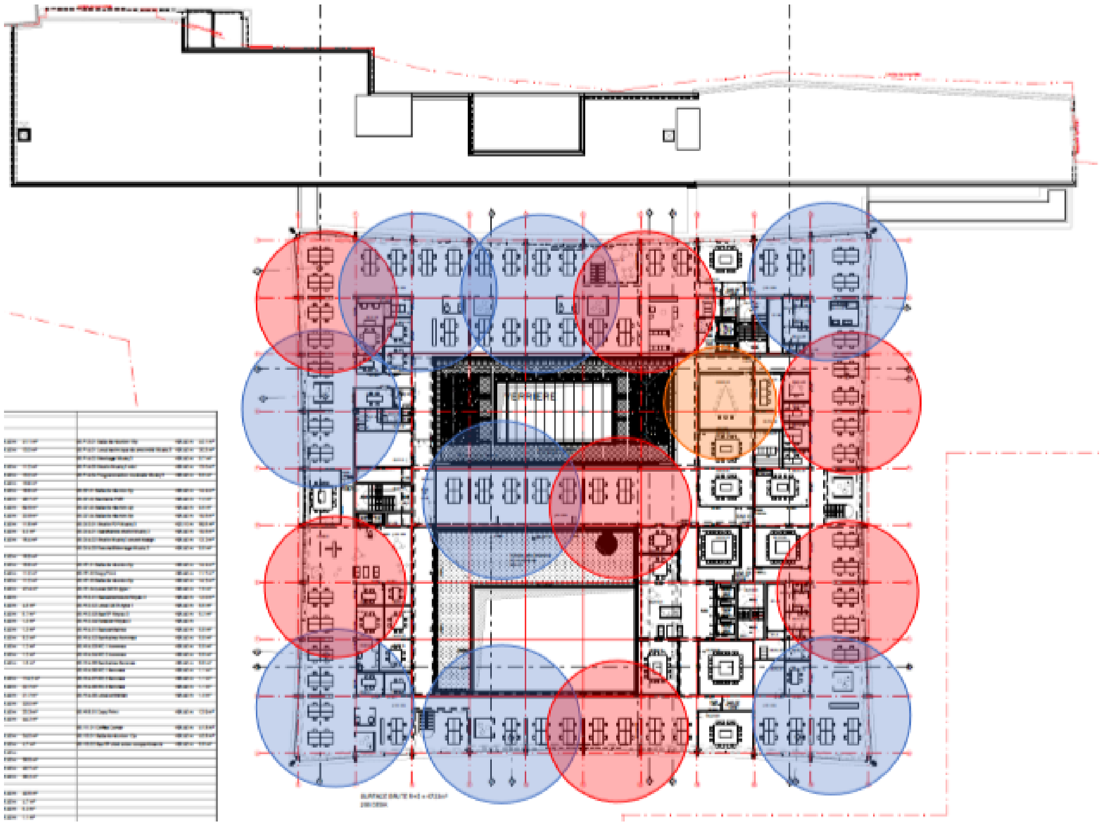

Figure 111 Coverage Access Points for Floor 5 in the Best Case

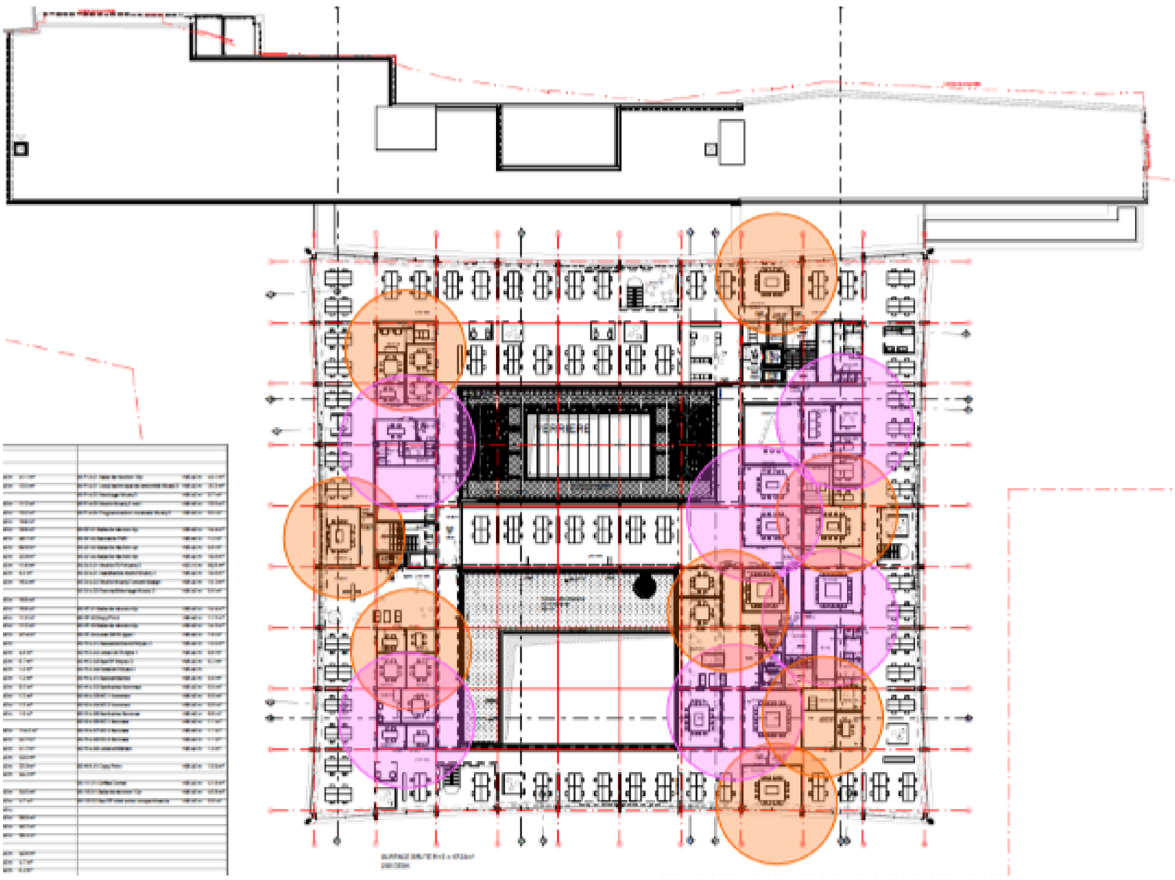

Figure 112 Coverage Access Points for Floor 5 in the Best Case

❖ Sixth Floor

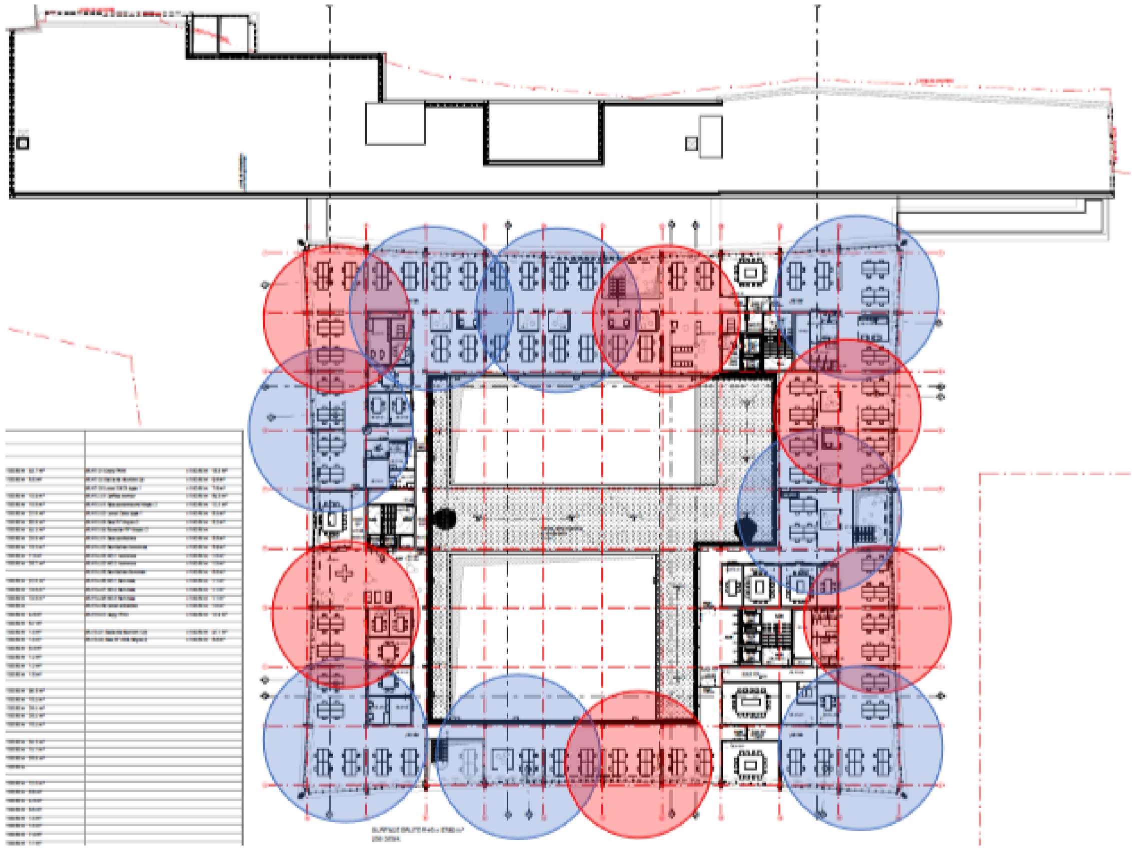

Figure 113 Coverage Access Points for Floor 6 in the Best Case

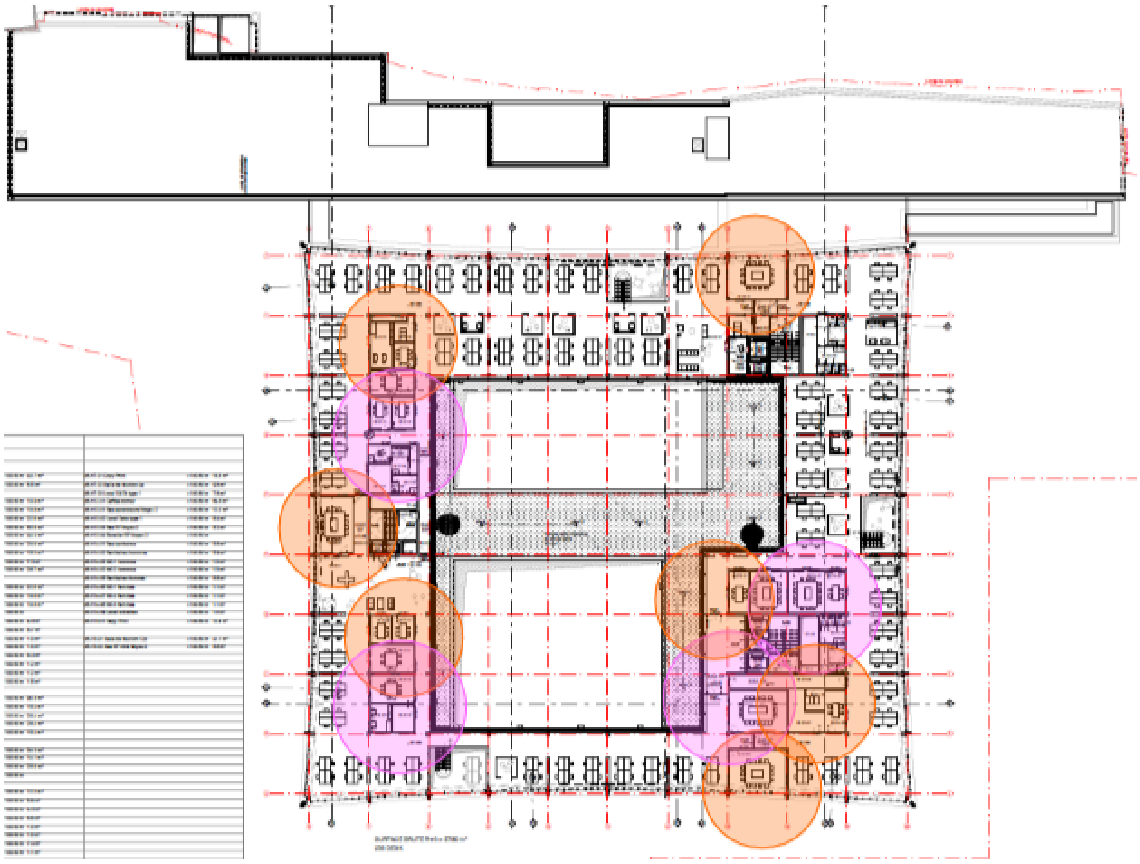

Figure 114 Coverage Access Points for Floor 6 in the Best Case

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Annex 1 Cisco Aironet 2700 Series Access Points Datasheet: Data Rates of 802.11n Standard at 2.4 GHz

802.11n data rates on 2.4 GHz:			
MCS Index[1]	GI[2] = 800 ns	GI = 400 ns	
	20-MHz Rate (Mbps)	20-MHz Rate (Mbps)	
0	6.5	7.2	
1	13	14.4	
2	19.5	21.7	
3	26	28.9	
4	39	43.3	
5	52	57.8	
6	58.5	65	
7	65	72.2	
8	13	14.4	
9	26	28.9	
10	39	43.3	
11	52	57.8	
12	78	86.7	
13	104	115.6	
14	117	130	
15	130	144.4	
16	19.5	21.7	
17	39	43.3	
18	58.5	65	
19	78	86.7	
20	117	130	
21	156	173.3	
22	175.5	195	
23	195	216.7	

Table 25 Data Rates of 802.11n Standard at 2.4 GHz [15]

Annex 2 Cisco Aironet 2700 Series Access Points Datasheet: Data Rates of 802.11ac Standard at 5 GHz

802.11ac data rates (5 GHz):							
MCS Index[3]	Spatial Streams	GI[4] = 800ns			GI = 400ns		
		20-MHz Rate (Mbps)	40-MHz Rate (Mbps)	80-MHz Rate (Mbps)	20-MHz Rate (Mbps)	40-MHz Rate (Mbps)	80-MHz Rate (Mbps)
0	1	6.5	13.5	29.3	7.2	15	32.5
1	1	13	27	58.5	14.4	30	65
2	1	19.5	40.5	87.8	21.7	45	97.5
3	1	26	54	117	28.9	60	130
4	1	39	81	175.5	43.3	90	195
5	1	52	108	234	57.8	120	260
6	1	58.5	121.5	263.3	65	135	292.5
7	1	65	135	292.5	72.2	150	325
8	1	78	162	351	86.7	180	390
9	1	-	180	390	-	200	433.3
0	2	13	27	58.5	14.4	30	65
1	2	26	54	117	28.9	60	130
2	2	39	81	175.5	43.3	90	195
3	2	52	108	234	57.8	120	260
4	2	78	162	351	86.7	180	390
5	2	104	216	468	115.6	240	520
6	2	117	243	526.5	130	270	585
7	2	130	270	585	144.4	300	650
8	2	156	324	702	173.3	360	780
9	2	78	780	780	-	400	866.7
0	3	19.5	40.5	87.8	21.7	45	97.5
1	3	39	81	175.5	43.3	90	195
2	3	58.5	121.5	263.3	65	135	292.5
3	3	78	162	351	86.7	180	390
4	3	117	243	526.5	130	270	585
5	3	156	324	702	173.3	360	780
6	3	175.5	364.5	-	195	405	-
7	3	195	405	877.5	216.7	450	975
8	3	234	486	1053	260	540	1170
9	3	260	540	1170	288.9	600	1300

Table 26 Data Rates of 802.11ac Standard at 5 GHz [15]

Annex 3 IUT-R P.1238 "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz"

This annex includes the datas and formulas from the IUT-R P.1238 that were used in this End-of-Grade project.

The basic model has the following form:

$$L_{total} = L(d_o) + N\log_{10}\frac{d}{d_o} + L_f(n) \qquad \text{dB} \qquad (1)$$

where:

- N: distance power loss coefficient
- f: frequency (MHz)
- d: separation distance (m) between the base station and portable terminal (where $d > 1$ m)
- d_o: reference distance (m)
- $L(d_o)$: path loss at d_o (dB), for a reference distance d_o at 1 m, and assuming free-space propagation $L(d_o) = 20\log_{10} f - 28$ where f is in MHz
- L_f: floor penetration loss factor (dB)
- n: number of floors between base station and portable terminal ($n \geq 0$), $L_f = 0$ dB for $n = 0$.

Figure 115 Path Loss Basic Model Formula [3]

Power loss coefficients, N, for indoor transmission loss calculation

Frequency (GHz)	Residential	Office	Commercial	Factory	Corridor	Data Centre
0.8	–	22.5[14]	–	–	–	–
0.9	–	33	20	–	–	–
1.25	–	32	22	–	–	–
1.9	28	30	22	–	–	–
2.1	–	25.5[4]	20	21.1	17[9]	–
2.2	–	20.7[14]	–	–	–	–
2.4	28	30	–	–	–	–
2.625	–	44[5]	–	33[6]	–	–
3.5	–	27	–	–	–	–
4	–	28	22	–	–	–
4.7	–	19.8[14]	–	–	–	–
5.2	30[2] 28[3]	31	–	–	–	–
5.8	–	24	–	–	–	–
26	–	19.5[14]	–	–	–	–
28	–	18.4[12] 29.9[12]	27.6[8] 17.9[12, 13] 24.8[12, 13]	–	–	–
37	–	15.6[14]	–	–	–	–
38	–	20.3[12] 29.6[12]	18.6[12, 13] 25.9[12, 13]	–	–	–
51-57	–	15[10]	–	–	13[10] 16.3[4, 10]	–
60	–	22[1]	17[1]	–	16[1] [7][9]	–
67-73	–	19[11]	–	–	16[11] 17.6[4, 11]	–
70	–	22[1]	–	–	–	–
300	–	20[15]	–	–	19.5[9, 15]	20.2[15]

Table 27 Power Loss Coeficients 'N' [3]

Floor penetration loss factors, L_f (dB) with n being the number of floors penetrated, for indoor transmission loss calculation ($n \geq 1$)

Frequency (GHz)	Residential	Office	Commercial
0.9	–	9 (1 floor) 19 (2 floors) 24 (3 floors)	–
1.8-2	4 n	15 + 4 (n – 1)	6 + 3 (n – 1)
2.4	10(1) (apartment) 5 (house)	14	–
3.5	–	18 (1 floor) 26 (2 floors)	–
5.2	13(1) (apartment) 7(2) (house)	16 (1 floor)	–
5.8	–	22 (1 floor) 28 (2 floors)	–

(1) Per concrete wall.

(2) Wooden mortar.

Table 28 Floor Penetration Loss Factors 'L_f' [3]

Shadow fading statistics, standard deviation (dB), for indoor transmission loss calculation

Frequency (GHz)	Residential	Office	Commercial
0.8	–	3.4(4)	–
1.8-2	8	10	10
2.2	–	2.3(4)	–
3.5	–	8	–
4.7	–	2.7(4)	–
5.2	–	12	–
5.8	–	17	–
26	–	2.8(4)	–
28	–	3.4(2) 6.6(2)	6.7(1) 1.4(2, 3) 6.4(2, 3)
37	–	2.4(4)	–
38	–	4.6(2) 6.8(2)	1.6(2, 3) 5.5(2, 3)
51-57	–	2.7	–
67-73	–	2.1	–

Table 29 Standard Deviation [3]

Annex 4 IUT-R P.2040 "Effects of building materials and structures on Radiowave propagation above about 100 MHz"

This annex includes the informations from the IUT-R P.2040 that were used in this End-of-Grade project.

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Annex 2

1 Introduction

This Annex provides definitions of terms relating to building loss, and gives guidance on recommended measurement practices.

Report ITU-R P.2346 contains a compilation of the results of measurements of building entry loss.

2 Description of scenarios involving the outdoor-indoor interface

2.1 Outside-inside propagation: issues concerning entry-loss reference field

A difficulty with defining the entry loss reference field is that the presence of the building will modify signal strengths outside it. Figure A2.1 illustrates, in somewhat simplified form, the issues involved. The three sections of the figure show:

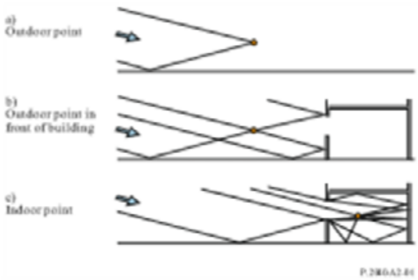
a) A relatively isolated outdoor point receives a direct and ground-reflected ray. In fact both of these rays, in an urban environment, may well arrive from a distant source via diffraction over a building to the left of the figure. For propagation at small angles to the horizontal, there will be fairly simply and mainly vertical lobing, that is, maxima and minima when the point is moved vertically.

b) Without moving the point, a building is placed just behind it. It now receives two additional rays reflected from the building, one of which is also ground-reflected. The lobing pattern will now have fine structure in both the vertical and horizontal directions.

c) The point is now moved inside the building. For the purposes of illustration the frequency is assumed to be high enough such that only rays entering a window are significant. At a lower frequency, where penetration through the wall is significant, the ray pattern would change.

FIGURE A2.1

Simplified ray diagrams for outdoor and indoor points



Although multipath propagation causes lobing, the power-sum of multiple rays approximates to the spatially-averaged field. In general, therefore, the presence of a building behind a receiver can be expected to increase the received signal strength. Inside the building, particularly close to the illuminated external wall, a larger number of rays is likely to be received, although many will be attenuated by transmission, reflection or diffraction. It is thus possible to have a stronger signal inside than outside.

Figure 116 First Page Annex 2 of the IUT-R P.2040 [4]

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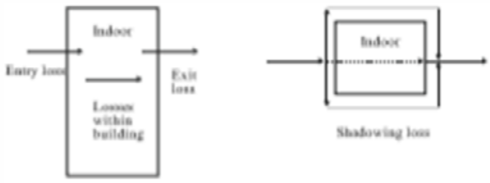
2.2 Propagation losses in the built environment

Figure A2.2 shows the different kinds of building losses encountered in an outdoor-indoor and indoor-outdoor scenario. The definitions are given in the next sections.

FIGURE A2.2

Different kinds of propagation loss involving buildings



3 Definitions

3.1 Definition of building entry loss

Building entry loss is the additional loss due to a terminal being inside a building.

3.2 Definition of building shadowing loss

The building shadowing loss is the difference between the median of the location variability of the signal level outside the illuminated face of a building and the signal level outside the opposite face of the building at the same height above ground, with multipath fading spatially averaged for both signals. It can be considered as the transmission loss through a building.

3.3 Definition of (e.g. wall) penetration

Signals outside a building enter an enclosed building by penetration mostly through walls. Wall penetration can also refer to the penetration through partitions inside buildings. Inside buildings, wall penetration loss is the difference between the median of the location variability of the signal level on one side of a wall, and the signal level on the opposite side of the wall at the same height above ground, with multipath fading spatially averaged for both signals. It can be considered as the transmission loss through a wall.

3.4 Definition of aperture penetration

Aperture penetration is the penetration of signals from one side of a wall to the other side through openings on the walls like windows.

3.5 Definition of building exit loss

From reciprocity, the numerical value of building exit loss will be the same as the building entry loss. In the remainder of this text the terms are used interchangeably.

Figure 117 Second Page Annex 2 of the IUT-R P.2040 [4]

Annex 5 Material Losses

This annex includes all the covering distances depending on the obstacles in the path and the antenna gain.

Attenuation	Coverage Distance		
	Antenna Gain 4 dBi	Antenna Gain 5 dBi	Antenna Gain 6 dBi
none	15,2465 m	16,422 m	17,688 m
3 dB	12,201 m	13,1418 m	14,155 m
7 dB	9,065 m	9,7638 m	10,5167 m
20 dB	3,4515 m	3,7176 m	4,0043 m
6 dB	9,7639 m	10,5167 m	11,3276 m
9 dB	7,8136 m	8,416 m	9,0649 m
14 dB	5,3896 m	5,805 m	6,2528 m
10 dB	7,254 m	7,8136 m	8,416 m
17 dB	4,313 m	4,6456 m	5,0038 m
8 dB	8,416 m	9,045 m	9,7639 m
12 dB	6,2527 m	6,7349 m	7,2542 m
13 dB	5,8052 m	6,2528 m	6,735 m
30 dB	1,6422 m	1,7688 m	1,905 m

Table 30 Covering Distances for the Obstacles Found at 5 GHz

Attenuation	Coverage Distance		
	Antenna Gain 4 dBi	Antenna Gain 5 dBi	Antenna Gain 6 dBi
none	25,1078 m	27,044 m	29,1289 m
3 dB	20,0925 m	21,642 m	23,31 m
7 dB	14,928 m	16,079 m	17,3188 m
20 dB	5,684 m	6,122 m	6,59 m
6 dB	16,079 m	17,3188 m	18,6542 m
9 dB	12,8673 m	13,8594 m	14,928 m
14 dB	8,8756 m	9,56 m	10,297 m
10 dB	11,946 m	10,867 m	13,859 m
17 dB	7,103 m	7,65 m	8,2402 m
8 dB	13,8594 m	14,928 m	16,079 m
12 dB	10,297 m	11,09 m	11,946 m
13 dB	9,56 m	10,297 m	11,091 m
30 dB	2,704 m	2,913 m	3,1375 m

Table 311 Covering Distances for the Obstacles Found at 2.4 GHz

Annex 6 Placement and Operating Band of Each Access Point for a Wi-Fi Network in the Current Building

The APs are represented by a red point and are referred by a number for each floor. Those APs are also described in tables by model, placement and operating band. The APs preceded by the * symbol correspond to delicate locations such as radio and television studios. Their operating frequency band need more information to be define to avoid interferences.

- Building CHJM
  - ❖ Eleventh Floor

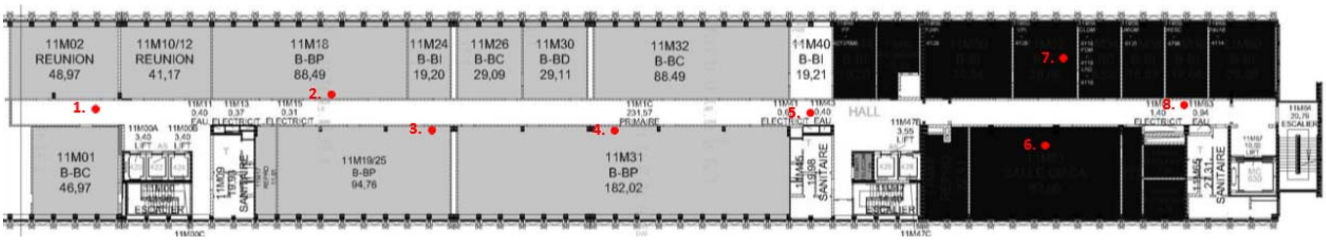


Figure 118 Placement Access Points for Floor 11 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
11.1	RE-11M01	2700E	Dual band
11.2	RE-11M18	2800E	5 GHz only
11.3	RE-11M25	2800E	Dual band
11.4	RE-11M31	2700I	5 GHz only
11.5	RE-11M40	2800E	Dual band
11.6	RE-11M51	3600I	Dual band
11.7	RE-11M52	2700I	Dual band
11.8	RE-11M58	2800E	Dual band

Table 32 Placement Access Points for Floor 11 in Building CHJM

  - ❖ Tenth Floor

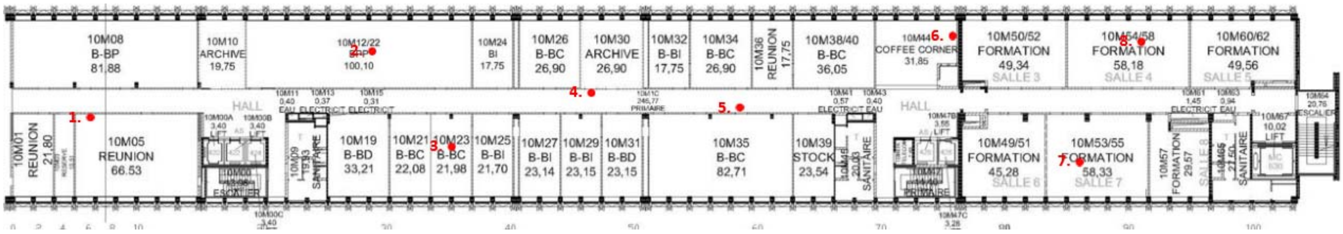


Figure 119 Placement Access Points for Floor 10 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
10.1	RE-10M05	2800E	Dual band
10.2	RE-10M20	2700I	5 GHz only
10.3	RE-10M23	2800E	Dual band
10.4	RE-10M30	2800E	5 GHz only
10.5	RE-10M35	2800E	Dual band
10.6	RE-10M44	2800E	5 GHz only
10.7	RE-10M55	2700I	Dual band
10.8	RE-10M58	2800E	Dual band

Table 33 Placement Access Points for Floor 10 in Building CHJM

❖ Ninth Floor

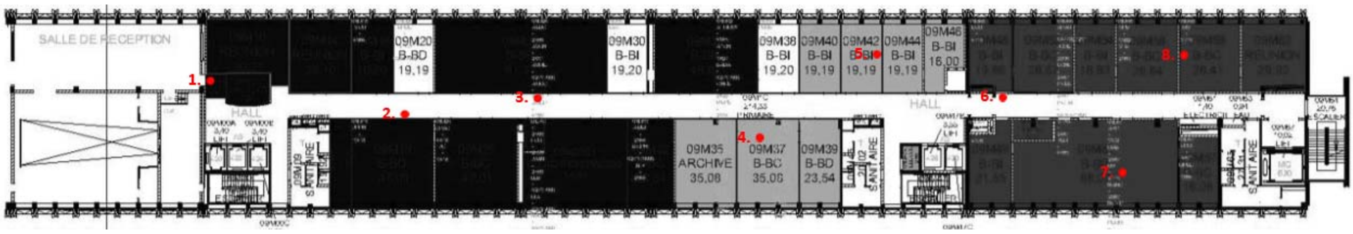


Figure 120 Placement Access Points for Floor 9 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
9.1	RE-09M06	2800E	Dual band
9.2	RE-09M19	2700I	5 GHz only
9.3	RE-09M26	2800E	Dual band
9.4	RE-09M37	2800E	5 GHz only
9.5	RE-09M42	2800E	Dual band
9.6	RE-09M48	2800E	5 GHz only
9.7	RE-09M51	2700I	Dual band
9.8	RE-09M58	2800E	Dual band

Table 34 Placement Access Points for Floor 9 in Building CHJM

❖ Eighth Floor

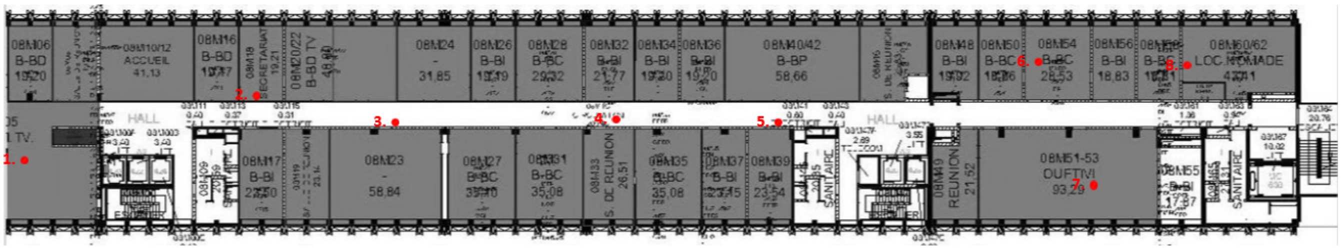


Figure 121 Placement Access Points for Floor 8 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
8.1	RE-08M05	2700I	Dual band
8.2	RE-08M18	2800E	Dual band
8.3	RE-08M24	2800E	5 GHz only
8.4	RE-08M33	2700I	Dual band
8.5	RE-08M40	2800E	Dual band
8.6	RE-08M53	2800E	Dual band
8.7	RE-08M54	2800E	Dual band
8.8	RE-08M60	2800E	Dual band

Table 335 Placement Access Points for Floor 8 in Building CHJM

❖ Seventh Floor

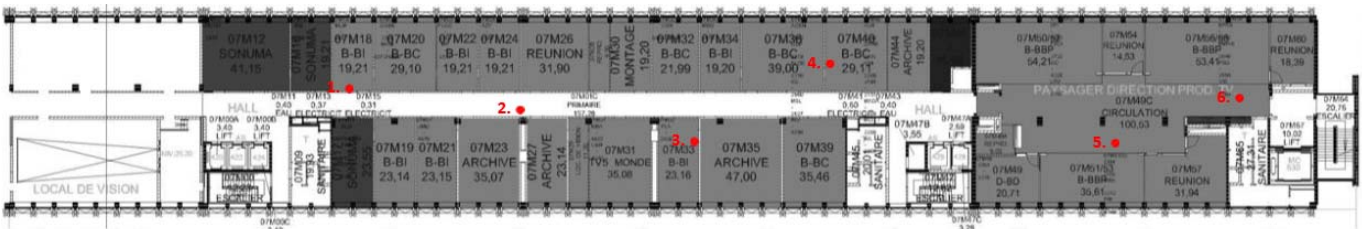


Figure 122 Placement Access Points for Floor 6 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
7.1	RE-07M18	2800E	2800E
7.2	RE-07M26	2800E	2800E
7.3	RE-07M33	2800E	2800E
7.4	RE-07M40	2800E	2800E
7.5	RE-07M49-1	3600I	3600I
7.6	RE-07M49-2	2700I	2700I

Table 36 Placement Access Points for Floor 7 in Building CHJM

❖ Sixth Floor

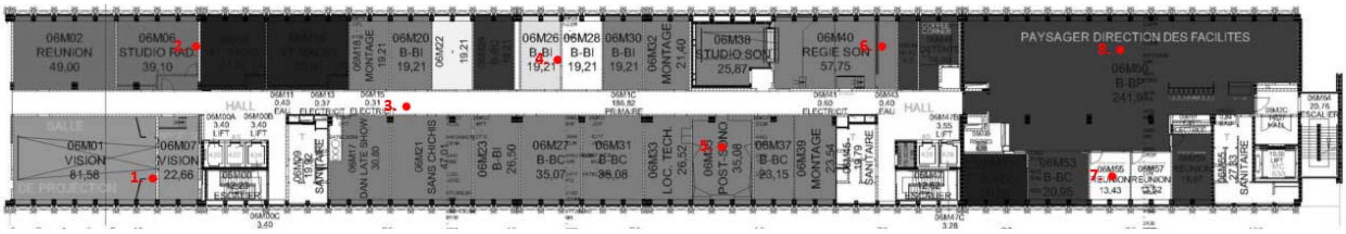


Figure 123 Placement Access Points for Floor 6 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
6.1	RE-06M01	2800E	5 GHz only
6.2	RE-06M06	2800E	Dual band
6.3	RE-06M20	2700I	Dual band
6.4	RE-06M26	2700E	Dual band
6.5	RE-06M35	2800E	Dual band
6.6	RE-06M40	2800E	Dual band
6.7	RE-06M55	2800E	Dual band
6.8	RE-06M50	2700E	5 GHz only

Table 37 Placement Access Points for Floor 6 in Building CHJM

❖ Fifth Floor

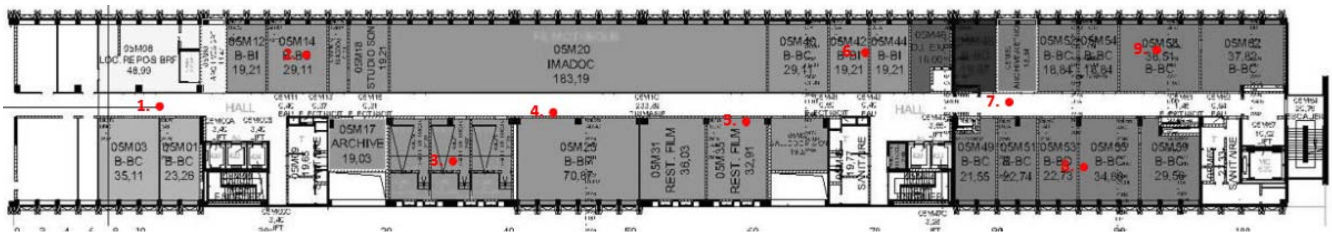


Figure 124 Placement Access Points for Floor 5 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
5.1	RE-05M03	3600I	Dual band
5.2	RE-05M14	2800E	Dual band
5.3	RE-05M21	2800E	Dual band
5.4	RE-05M25	2800E	Dual band
5.5	RE-05M35	2800E	Dual band
5.6	RE-05M42	3600I	Dual band
5.7	RE-05M51	2700I	Dual band
5.8	RE-05M55	2800E	Dual band
5.9	RE-05M58	2800E	Dual band

Table 348 Placement Access Points for Floor 5 in Building CHJM

- Fourth Floor

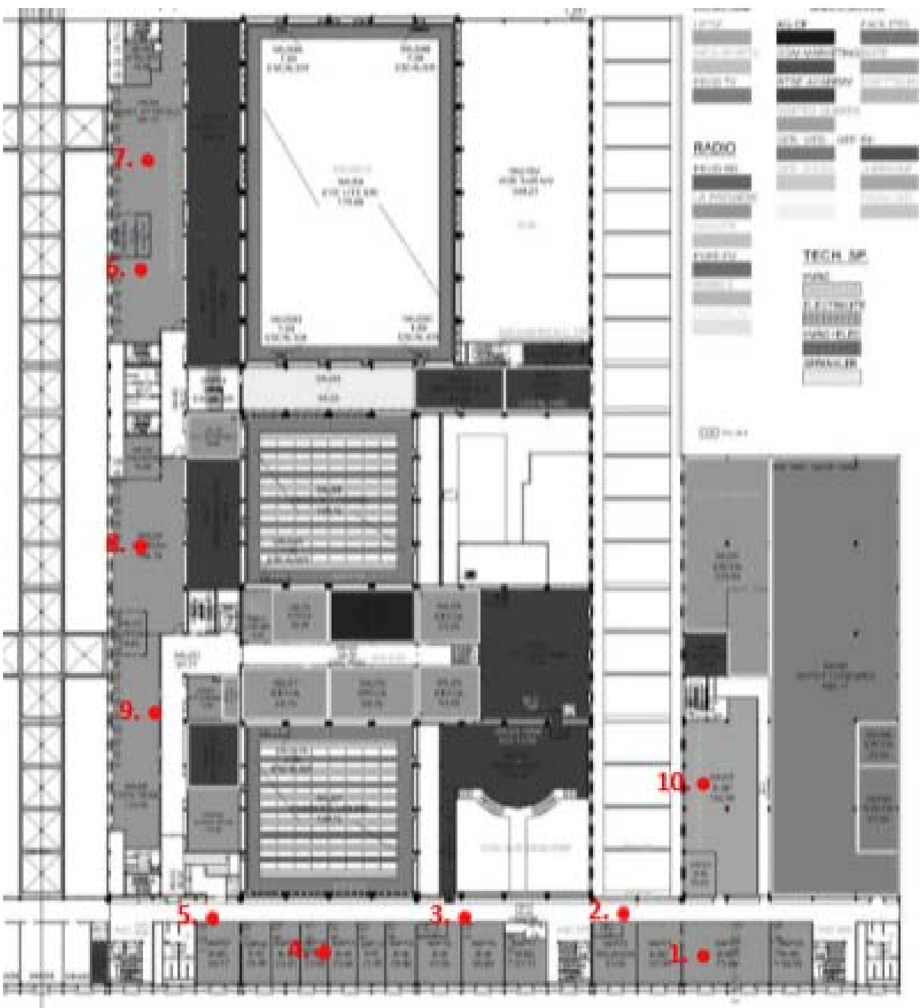


Figure 125 Placement Access Points for Floor 4 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
4.1	RE-04P22	2800E	Dual band
4.2	RE-04P20	3600I	5 GHz only
4.3	RE-04P16	2700I	Dual band
4.4	RE-04P11	2700I	Dual band
4.5	RE-04P07	2800E	5 GHz only
4.6	RE-04U34-1	2700I	5 GHz only
4.7	RE-04U34-2	2700I	Dual band
4.8	RE-04U26	2800E	Dual band
4.9	RE-04U04	2800E	Dual band
4.10	RE-04V01	2800E	Dual band

Table 359 Placement Access Points for Floor 4 in Building CHJM

- Third Floor

Figure 126 Placement Access Points for Floor 3 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
3.1	RE-03P03	2800E	Dual band
3.2	RE-03P08	2800E	Dual band
3.3	RE-03P12	2800E	5 GHz only
3.4	RE-03P16	2800E	Dual band
3.5	RE-03P20	2800E	Dual band
3.6	RE-03P23	2800E	Dual band
3.7	RE-MESS	2700I	Dual band
3.8	RE-03U32	2800E	Dual band
3.9	RE-03U15	2600E	Dual band

Table 40 Placement Access Points for Floor 3 in Building CHJM

❖ Second Floor

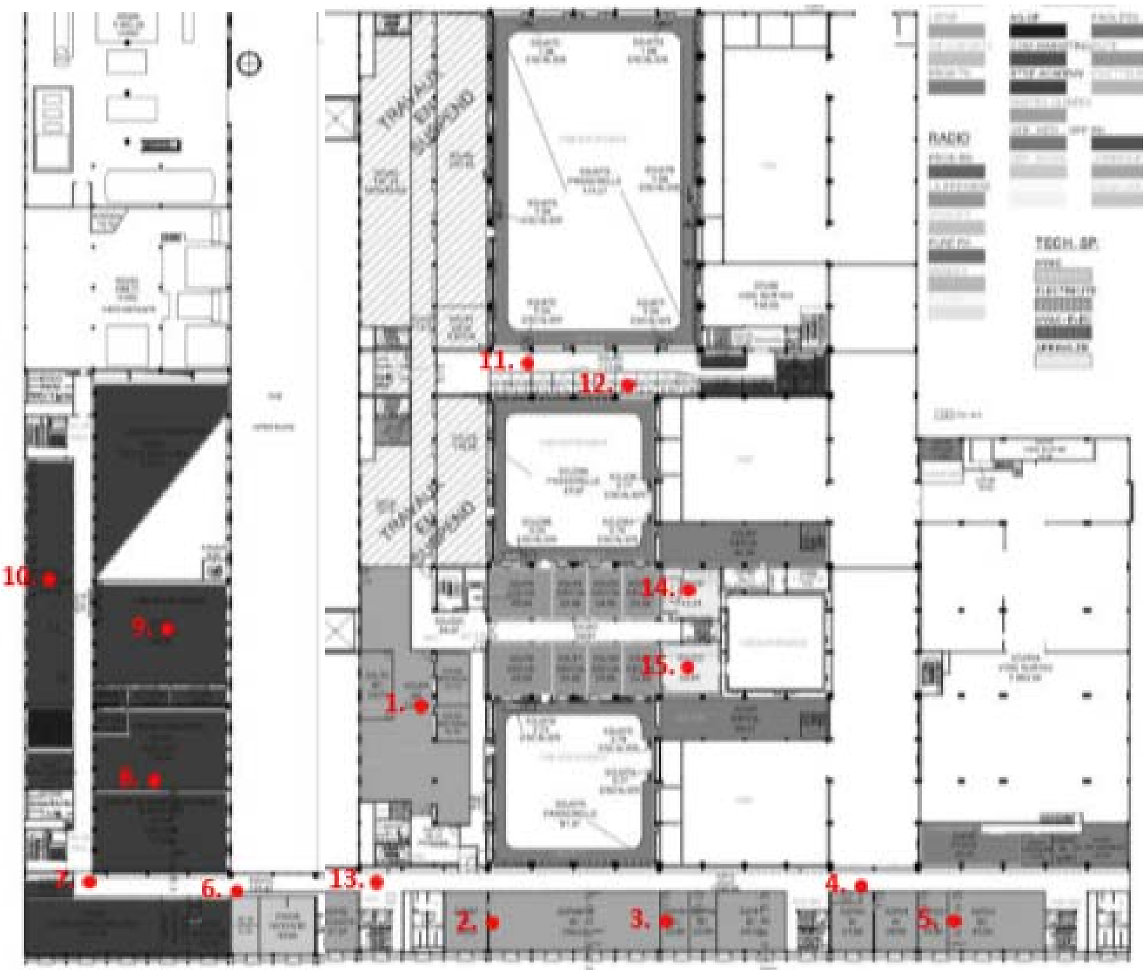


Figure 127 Placement Access Points for Floor 2 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
2.1	RE-02U01	2700E	Dual band
2.2	RE-02P10	2800I	Dual band
2.3	RE-02P14	2700I	Dual band
2.4	RE-02P20	2800E	5 GHz only
2.5	RE-02P22	2800E	Dual band
2.6	RE-02N30	2700E	Dual band
2.7	RE-02N34	2800E	Dual band
2.8	RE-02Q10	2800E	Dual band
2.9	RE-02Q14	2700I	Dual band
2.10	RE-02Q21	2700I	Dual band
2.11	RE-02U6C	2800E	Dual band
2.12	RE-02U74	2800E	Dual band
*2.13	RE-02P02	2800E	Dual band
*2.14	RE-02U26	2800E	
*2.15	RE-02U23	2800E	

Table 4136 Placement Access Points for Floor 2 in Building CHJM

❖ First Floor

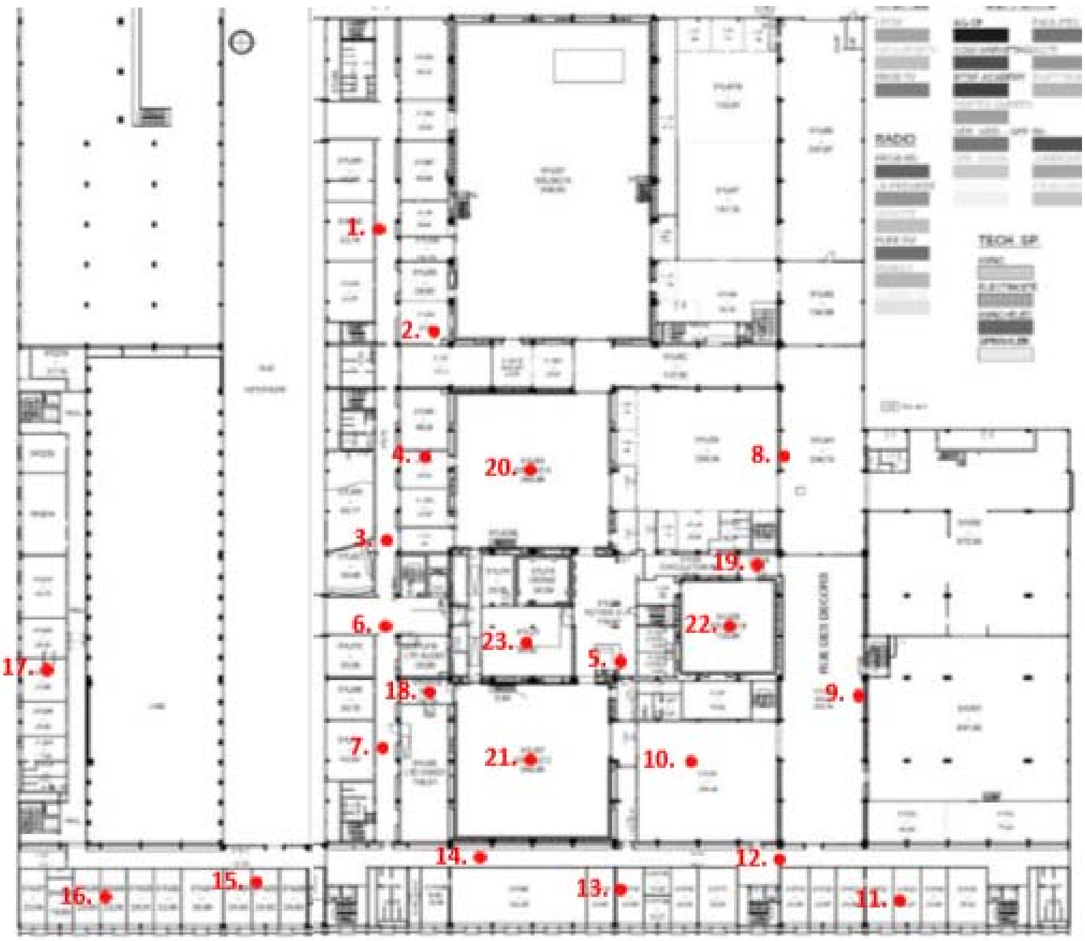


Figure 128 Placement Access Points for Floor 1 in Building CHJM

Access Point N°	Local Placement	Model	Operating band
1.1	RE-01U58	2800E	Dual band
1.2	RE-01U53	2800E	Dual band
1.3	RE-01U48	2800E	Dual band
1.4	RE-01U45	2800I	Dual band
1.5	RE-01U23	2700I	Dual band
1.6	RE-01U10	2800E	Dual band
1.7	RE-01U04	2800E	Dual band
1.8	RE-01U81	2800E	Dual band
1.9	RE-01U79	2800E	Dual band
1.10	RE-01U34	2800E	Dual band
1.11	RE-01P23	2800E	Dual band
1.12	RE-01P19	2800E	Dual band
1.13	RE-01P14	2800E	Dual band
1.14	RE-01P08	2800E	Dual band
1.15	RE-01N29	2800E	Dual band
1.16	RE-01N34	2800E	Dual band
1.17	RE-01Q07	2800E	Dual band
*1.18	SAS-STUDIO2	2800E	
*1.19	SAS-STUDIO8	2800E	
*1.20	STUDIO4	2800E	
*1.21	STUDIO2	2800E	
*1.22	STUDIO8	2800E	
*1.23	RE-01U21	2800E	

Table 42 Placement Access Points for Floor 1 in Building CHJM

❖ Ground Floor

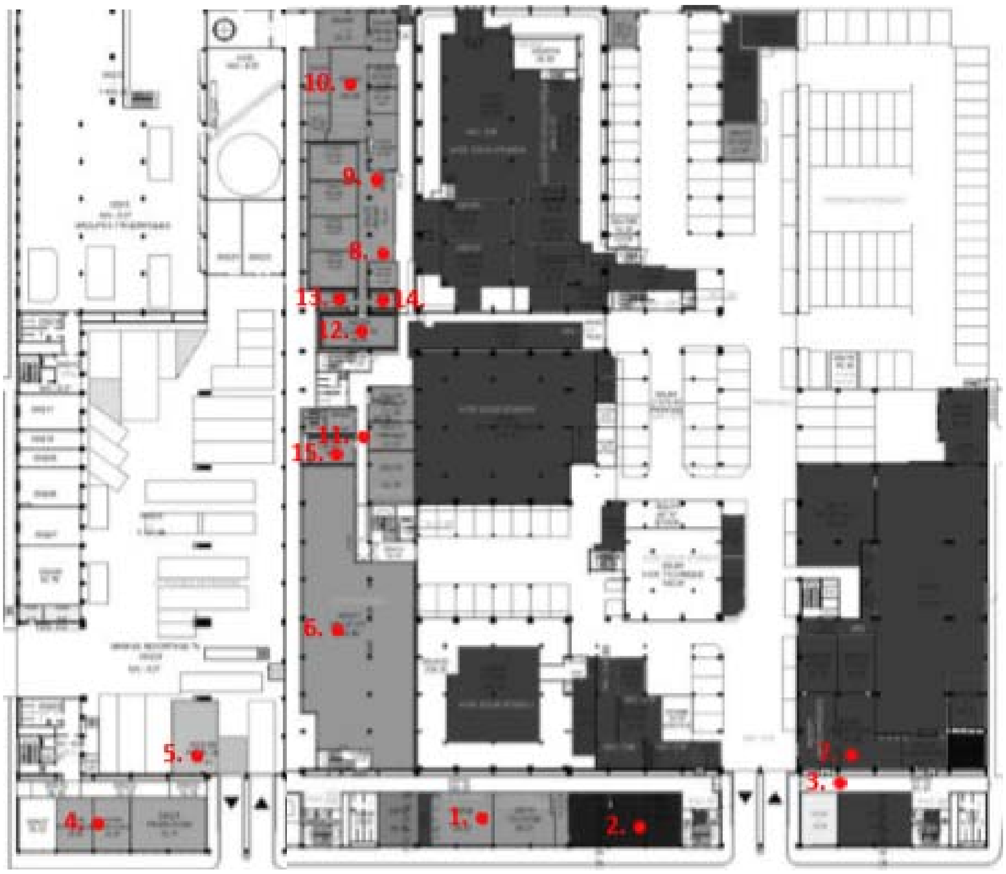


Figure 129 Placement Access Points for Ground Floor in Building CHJM

Access Point N°	Local Placement	Model	Operating band
0.1	RE-00P08	2800E	Dual band
0.2	RE-00P16	2800E	Dual band
0.3	RE-00P22	2800E	Dual band
0.4	RE-00N34	2800E	Dual band
0.5	RE-00Q20B	2800E	Dual band
0.6	RE-00U01	2700I	Dual band
0.7	RE-00V01	2800E	Dual band
0.8	RE-00U35-1	2800E	Dual band
0.9	RE-00U35-2	2800E	Dual band
0.10	RE-00U40	2700I	Dual band
0.11	RE-00U17	2700I	Dual band
*0.12	RE-00U26	2800E	Dual band
*0.13	RE-00U22	2800E	Dual band
*0.14	RE-00U20	2800E	Dual band
*0.15	RE-00U18	2800E	Dual band

Table 4337 Placement Access Points for Ground Floor in Building CHJM

- Building PUVQ
  - ❖ Fourth Floor

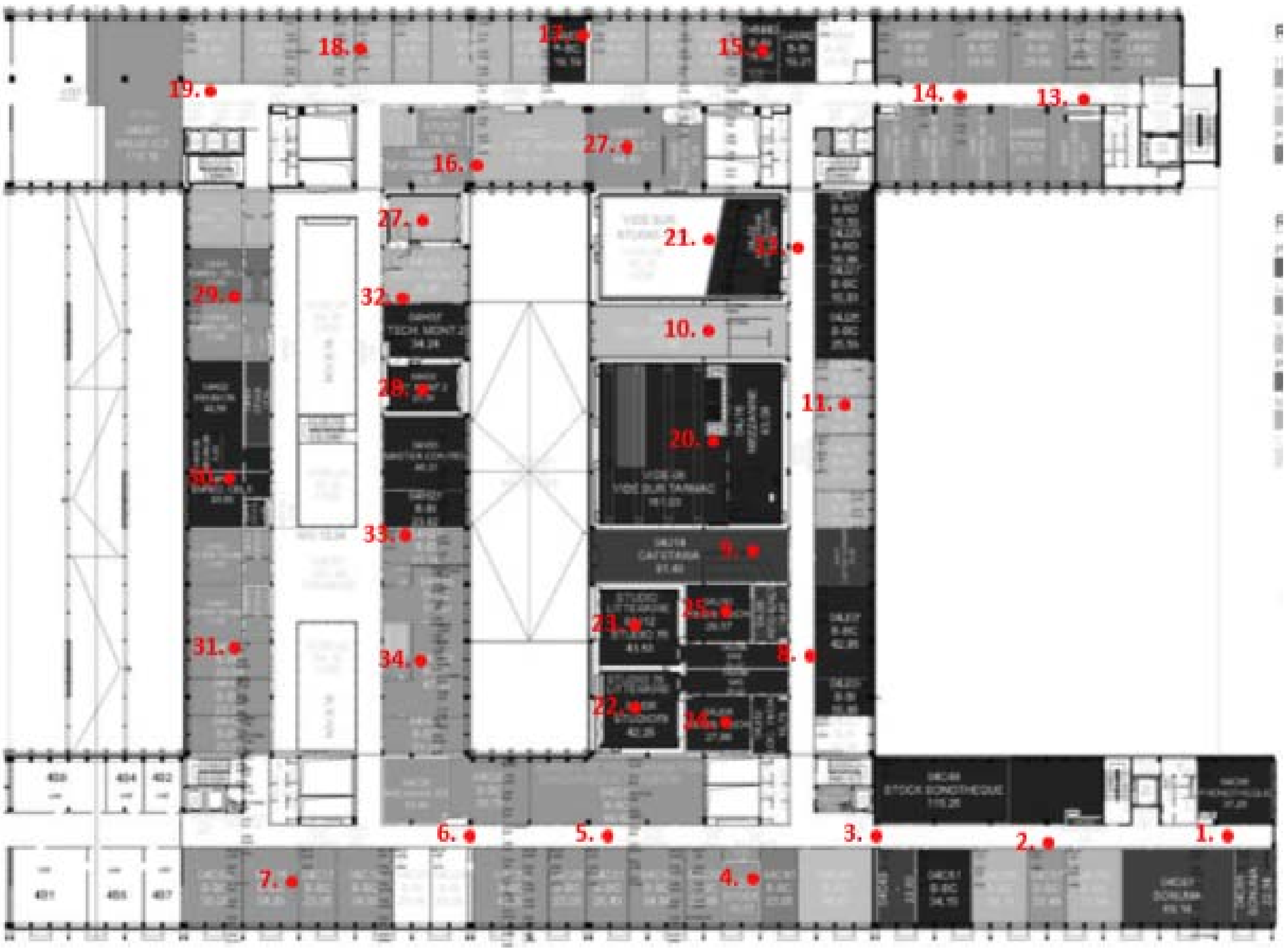


Figure 130 Placement Access Points for Floor 4 in Building PUVQ

Access Point N°	Local Placement	Model	Operating band
4.1	RE-04C63	2800E	Dual band
4.2	RE-04C57	2800E	Dual band
4.3	RE-04C49	3600I	Dual band
4.4	RE-04C39	2600E	5 GHz only
4.5	RE-04C31	2800E	Dual band
4.6	RE-04C26	2800E	5 GHz only
4.7	RE-04C15	2800E	Dual band
4.8	RE-04J07	2800E	Dual band
4.9	RE-04J14	2800E	Dual band
4.10	RE-04J20	2800E	Dual band
4.11	RE-04J21	2800E	Dual band
4.12	RE-04J29	2800E	Dual band
4.13	RE-04M60	2800E	Dual band
4.14	RE-04M54	2800E	Dual band
4.15	RE-04M40	2700I	Dual band
4.16	RE-04M23	2700I	Dual band
4.17	RE-04M30	2800E	Dual band
4.18	RE-04M20	2800E	Dual band
4.19	RE-04M10	2800E	Dual band
4.20	TARMAC	2800E	Dual band
4.21	TALK	2800E	Dual band
4.22	RE-04J06	2800E	Dual band
4.23	RE-04J12	2800E	Dual band
4.24	RE-04J04	2800E	Dual band
4.25	RE-04J10	2800E	Dual band
4.26	RE-04M31	2800E	Dual band
4.27	RE-04H41	2800E	Dual band
4.28	RE-04H33	2800E	Dual band
4.29	RE-04H38	2800E	Dual band
4.30	RE-04H20	3600I	Dual band
4.31	RE-04H06	2800E	Dual band
4.32	RE-04H39	2800E	Dual band
4.33	RE-04H21	2800E	Dual band
4.34	RE-04H03	2800I	Dual band

Table 4438 Placement Access Points for Floor 4 in Building PUVQ

❖ Third Floor

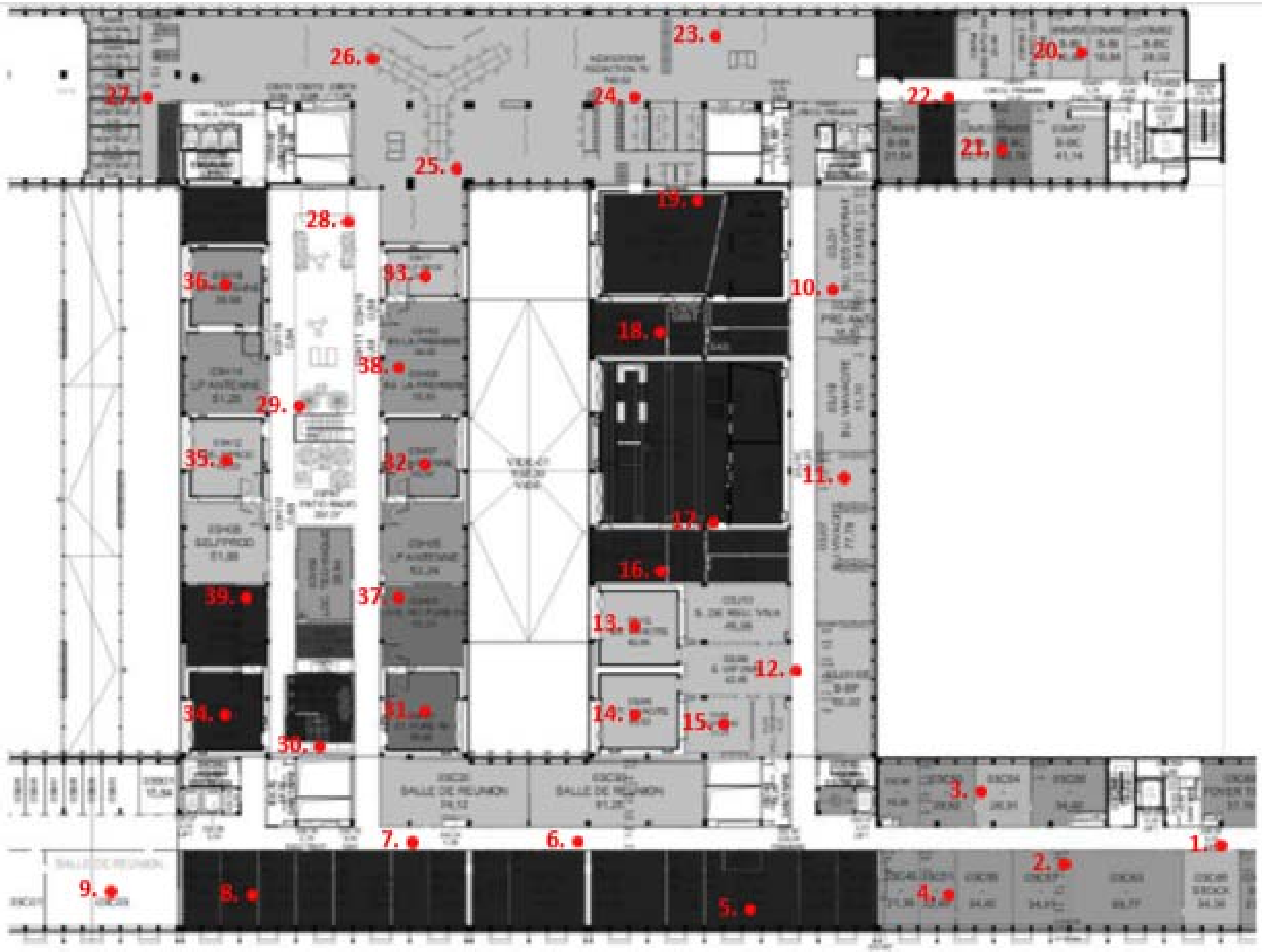


Figure 131 Placement Access Points for Floor 3 in Building PUVQ

Access Point N°	Local Placement	Model	Operating band
3.1	RE-03C65	2800E	Dual band
3.2	RE-03C57	2800E	5 GHz only
3.3	RE-03C54	2800E	Dual band
3.4	RE-03C51	2800E	Dual band
3.5	RE-03C37	2800E	Dual band
3.6	RE-03C30	2700I	Dual band
3.7	RE-03C17	2800E	Dual band
3.8	RE-03C11	3600I	Dual band
3.9	RE-03C03	2800E	Dual band
3.10	RE-03J31	2700I	Dual band
3.11	RE-03J07	2800E	5 GHz only
3.12	RE-03J01	2700E	Dual band
3.13	RE-03J12	2700I	Dual band
3.14	RE-03J06	2800E	Dual band
3.15	RE-03J04	2700I	Dual band
3.16	RE-03J18	2800I	Dual band
3.17	RE-03J20	2800I	5 GHz only
3.18	RE-03J30	2800E	Dual band
3.19	RE-03J32	2600E	Dual band
3.20	RE-03M58	2700E	Dual band
3.21	RE-03M55	2700E	Dual band
3.22	RE-03M51	2700I	Dual band
3.23	RE-03M01-1	2700I	Dual band
3.24	RE-03M01-2	2700I	5 GHz only
3.25	RE-03M01-3	2700I	Dual band
3.26	RE-03M01-4	2800I	Dual band
3.27	RE-03M01-5	2800I	Dual band
3.28	RE-PATIO-1	2800E	5 GHz only
3.29	RE-PATIO-2	2800E	Dual band
3.30	RE-PATIO-3	2800E	5 GHz only
3.31	RE-03H01	3600I	Dual band
3.32	RE-03H07	2800E	Dual band
3.33	RE-03H17	2800E	Dual band
3.34	RE-03H02	2800E	Dual band
3.35	RE-03H12	2700E	Dual band
3.36	RE-03H18	2700I	Dual band
3.37	RE-03H03	2800E	Dual band
3.38	RE-03H09	2700I	Dual band
3.39	RE-03H06	2700I	Dual band

Table 4539 Placement Access Points for Floor 3 in Building PUVQ

❖ Second Floor

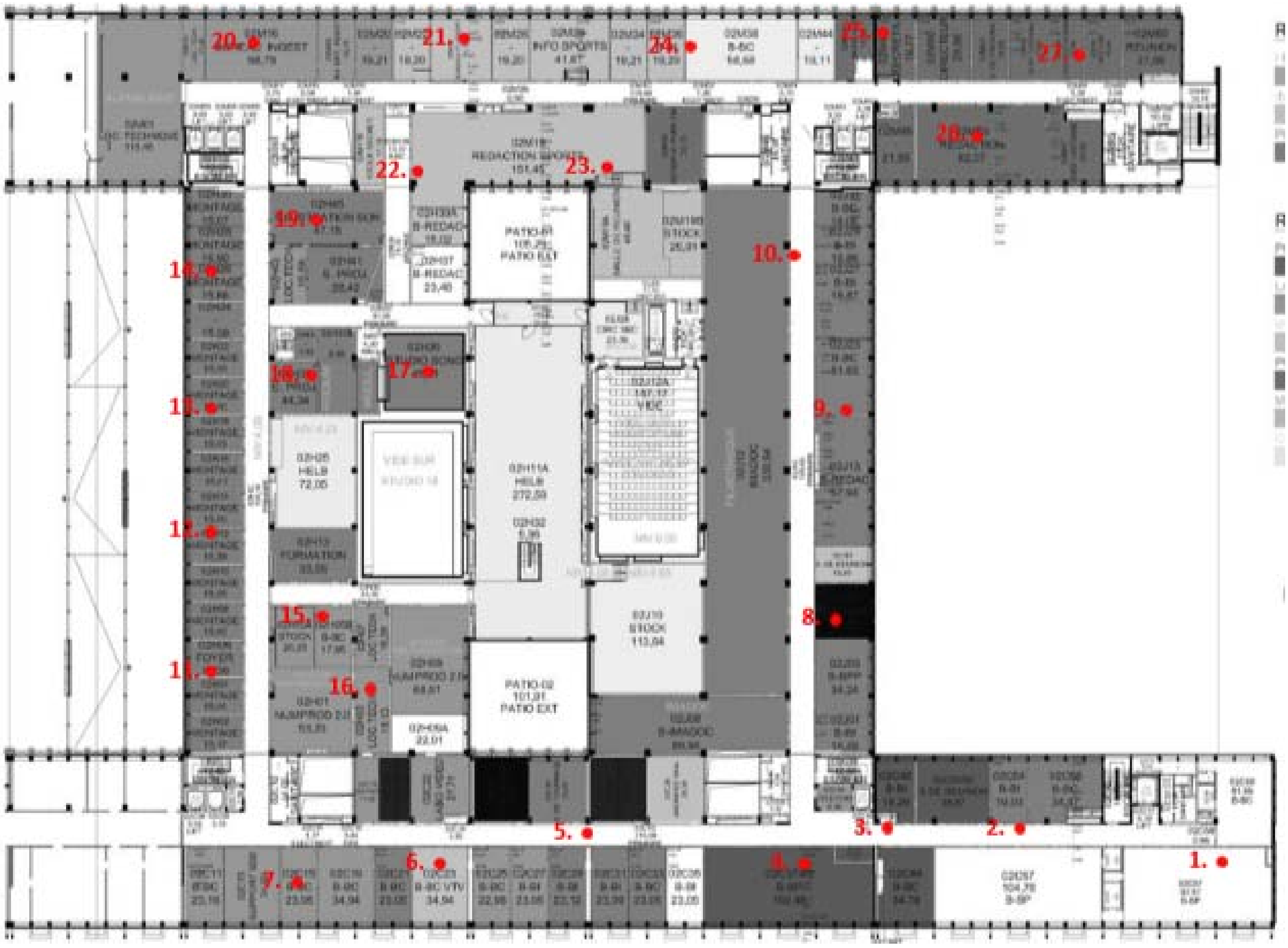


Figure 132 Placement Access Points for Floor 2 in Building PUVQ

Access Point N°	Local Placement	Model	Operating band
2.1	RE-02C67	2700I	Dual band
2.2	RE-02C54	2800E	Dual band
2.3	RE-02C48	2700I	Dual band
2.4	RE-02C37	2700I	Dual band
2.5	RE-02C29	2800E	Dual band
2.6	RE-02C23	2700I	5 GHz only
2.7	RE-02C15	2700I	Dual band
2.8	RE-02J07	2800E	Dual band
2.9	RE-02J23	2800E	5 GHz only
2.10	RE-02J29	2800E	Dual band
2.11	RE-02H06	2800E	Dual band
2.12	RE-02H12	2800E	Dual band
2.13	RE-02H20	2800E	Dual band
2.14	RE-02H26	2800E	Dual band
2.15	RE-02H05B	2600E	5 GHz only
2.16	RE-02H03	2600E	Dual band
2.17	RE-02H35	2800E	Dual band
2.18	RE-02H33	2800E	Dual band
2.19	RE-02H45	2800E	Dual band
2.20	RE-02M16	2800E	Dual band
2.21	RE-02M24	2800E	Dual band
2.22	RE-02M19-1	2800E	Dual band
2.23	RE-02M19-2	2800E	Dual band
2.24	RE-02M38	2800E	Dual band
2.25	RE-02M48	2700I	5 GHz only
2.26	RE-02M53	2700I	Dual band
2.27	RE-02M58	2700I	Dual band

Table 4640 Placement Access Points for Floor 2 in Building PUVQ

❖ First Floor

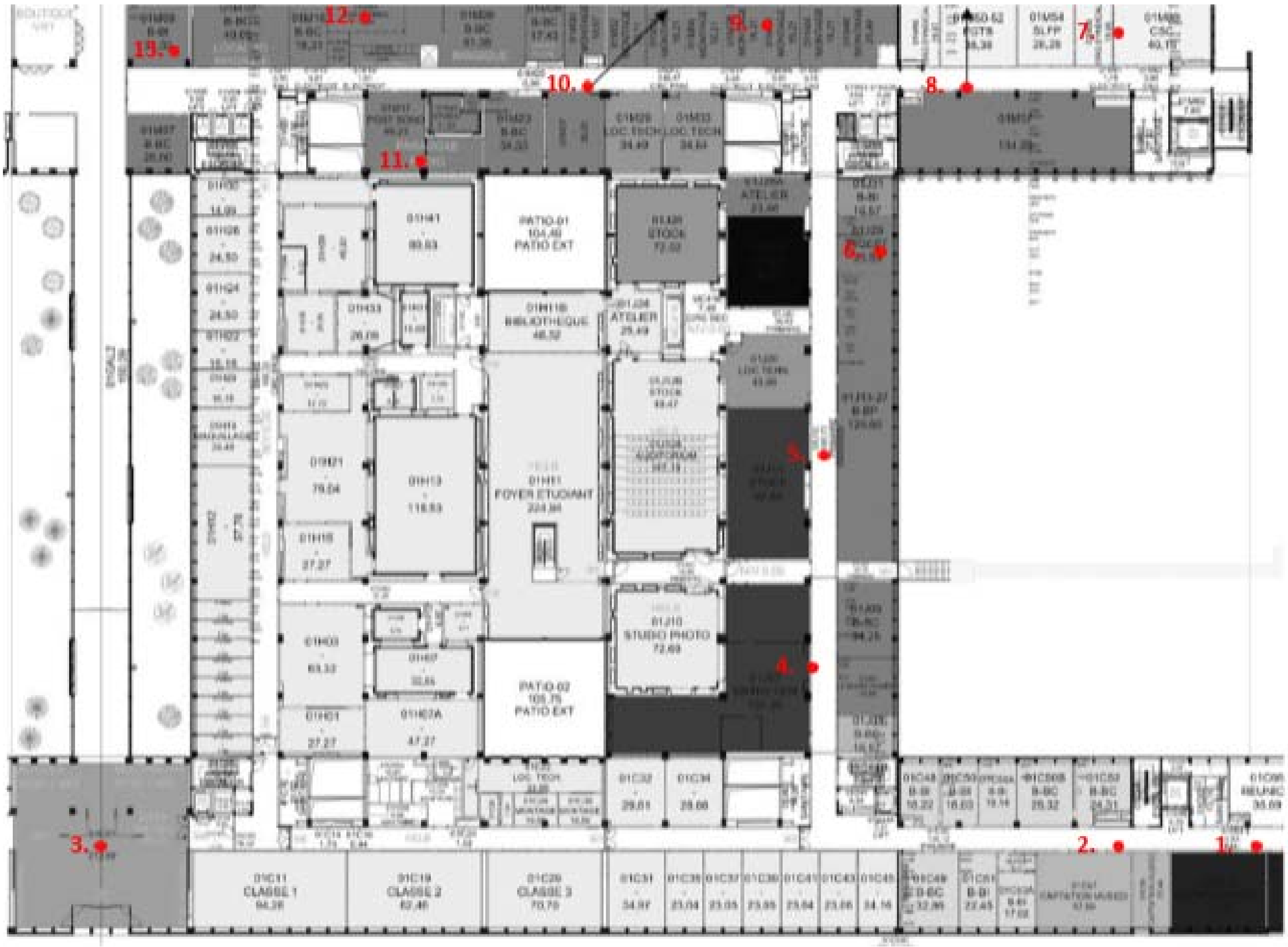


Figure 133 Placement Access Points for Floor 1 in Building PUVQ

Access Point N°	Local Placement	Model	Operating band
1.1	RE-01C66	2700I	Dual band
1.2	RE-01C57	2800E	Dual band
1.3	RE-HALLBC	2700I	Dual band
1.4	RE-01J03	2800E	Dual band
1.5	RE-01J13	2800E	Dual band
1.6	RE-01J29	2800E	Dual band
1.7	RE-01M60	2800E	Dual band
1.8	RE-01M57	2700I	Dual band
1.9	RE-01M40	2800E	Dual band
1.10	RE-01M27	2700I	Dual band
1.11	RE-01M17	2700I	Dual band
1.12	RE-01M18A	2700I	Dual band
1.13	RE-01M08	2800E	Dual band

Table 4741 Placement Access Points for Floor 1 in Building PUVQ

❖ Ground Floor

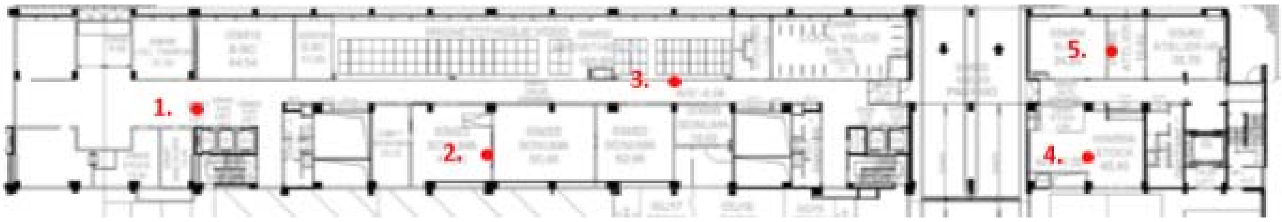


Figure 134 Placement Access Points for Ground Floor in Building PUVQ

Access Point N°	Local Placement	Model	Operating band
0.1	RE-00M10	2700I	Dual band
0.2	RE-00M23	2800E	Dual band
0.3	RE-00M33	2800E	Dual band
0.4	RE-00M55A	2800E	Dual band
0.5	RE-00M56	2800E	Dual band

Table 4842 Placement Access Points for GroundFloor in Building PUVQ

Model of access point	Number needed
2600E	5
2700E	9
2700I	47
2800E	168
2800I	7
3600I	9

Table 4943 Total Access Points Series Needed

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