

AUTONOMOUS MONITORING OF 5G RADIO-FREQUENCY ELECTROMAGNETIC FIELD EXPOSURE USING A QUADCOPTER

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AUTONOME MONITORING VAN 5G RADIOFREQUENTE ELEKTROMAGNETISCHE VELDBLOOTSTELLING MET EEN QUADCOPTER

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Explanation Regarding the Oral Defense

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

Abstract

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Program: Master of Science in Electrical Technology – Automation

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This master's dissertation presents the development and deployment of an autonomous quadcopter equipped with a frequency-selective triaxial 5G NR sensor for measuring radio-frequency electromagnetic field (RF-EMF) exposure. The primary objective was to design a drone-based system capable of autonomously constructing a high-resolution vertical 2D exposure grid near a 5G base station. The study includes detailed analyses of interference effects from onboard electronics on the 5G NR sensor, as well as the shielding influence of the drone's mechanical components. A comprehensive *in situ* measurement campaign was carried out using a 2D 16-waypoint vertical grid in proximity to a TX antenna emitting at a frequency of 3.530 GHz with a transmit power of 18 dBm. Extensive calibration procedures for all drone's sensors (e.g., IMUs, compass, RC transmitter and RC receiver, etc...) ensured both accurate sensor performance and stable autonomous flight. The obtained results, visualized through spatial heat maps, revealed peak electric field strengths up to 4.25 V/m, confirming the system's effectiveness for autonomous RF-EMF exposure monitoring. This work contributes to knowledge of fully autonomous systems in research applications and for future exposure monitoring in next-generation wireless networks, including 5G and 6G.

Keywords: radio-frequency electromagnetic field (RF-EMF), 5G NR, RF-EMF exposure, autonomous drone, triaxial 5G sensor

AUTONOMOUS MONITORING OF 5G RADIO-FREQUENCY ELECTROMAGNETIC FIELD EXPOSURE USING A QUADCOPTER

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1. Introduction

The widespread rollout of 5G New Radio (NR) worldwide demands efficient monitoring of radio-frequency electromagnetic field (RF-EMF) exposure. Public health concerns about potential biological effects require accurate data to ensure compliance with exposure guidelines such as those set by ICNIRP. RF-EMF measurement methods, such as manual scanning with handheld exposimeters are labour-intensive and limited in capturing 3D spatial electric field variations near base station antennas at high altitudes.

The primary objective of this thesis is to develop an autonomous quadcopter integrated with a triaxial 5G sensor, aimed at improving the efficiency and consistency of 5G NR RF-EMF exposure measurements through a cost-effective approach. The secondary objective involves deploying the autonomous system in an *in situ* measurement campaign conducted near a 5G base station. During this campaign, a vertical 2D grid is mapped to characterize RF-EMF exposure, where both average (E_{avg}) and maximum (E_{max}) electric field strengths are measured and visualised using heat maps. These measurements are collected through a fully automated flight script, enabling the drone to systematically capture exposure data at predefined positions within the grid. The study also investigates potential interference from the drone's onboard electronics and the shielding effects caused by its mechanical structure on the measurement accuracy of the sensor. By focusing on the n78 frequency band, which is widely deployed for 5G services in Belgium, the research contributes to greater transparency in public health monitoring and provides valuable data for epidemiological studies.

The literature review identified the n78 frequency band (3.4–3.8 GHz) as crucial for 5G NR commercial

deployment in Belgium. Analysis of 5G NR technologies, including Massive MIMO, Orthogonal Frequency Division Multiplexing (OFDM) and beamforming, revealed their significant impact on RF distribution and spatial variability. The current scientific understanding of RF-EMF exposure highlights its potential biological impacts. Therefore the ICNIRP updated their standardized exposure guidelines in 2020, which set a reference level of 61.7 V/m for the general populations RF-EMF exposure [1].

To measure RF-EMF exposure accurately various sensor technologies were studied. Special attention was given to hardware-based frequency-selective triaxial sensors capable of capturing electric field strength in real-time. These were compared against other solutions like Software-Defined Radios (SDR) in terms of software and frequency spectrum. Van der Straeten et al. developed a frequency-selective, low-cost triaxial 5G RF-EMF exposure hardware sensor which is capable of measuring exposure induced by 5G communication in the n78 (3300–3800 MHz) and the n77 (3300–4200 MHz) frequency band up to 3900 MHz [2].

In the context of this thesis, drone-based measurement protocols and system architectures were reviewed. Previous projects utilizing hexacopters and octocopters with integrated exposimeters or spectrum analyzers were analyzed for system design and validation purposes. These studies underestimated the importance of considering drone-induced onboard electronic electromagnetic interference, which was later addressed in this thesis through specific onboard electronic influence and mechanical shielding experiments.

2. Materials and methods

A. Autonomous drone development and calibration

To assess 5G NR RF-EMF exposure in the n78 band (3.4–3.8 GHz), an autonomous quadcopter is developed and equipped with a frequency-selective triaxial 5G NR sensor developed by Van der Straeten et al. [2]. The drone platform is selected after comparative testing of three systems: an Arduino-based drone, a DJI S1000 octocopter, and the Holybro X500 V2 Pixhawk drone. The Holybro X500 V2 is ultimately selected for its optimal balance between modularity, cost, and performance. A 5G NR sensor mount is developed in Siemens NX and 3D printed in PLA. [Figure 2-1a](#) shows the Holybro X500 V2 from above and [Figure 2-1b](#) shows how the triaxial 5G sensor is assembled on the drone.

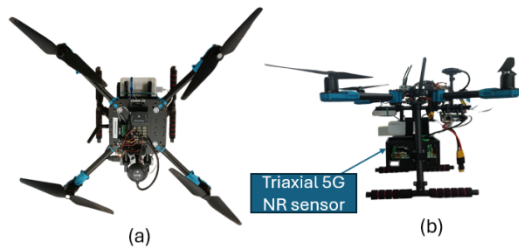


Figure 2-1: Holybro X500 V2 assembly with triaxial 5G NR sensor

The drone is equipped with a Pixhawk 6C flight controller, which serves as the central unit for flight control and sensor integration. Communication with the flight controller is established through multiple peripheral devices: a FlySky FS-i6 RC transmitter and a FlySky FS-iA6B receiver operating at 2.4 GHz for manual control, a telemetry radio module functioning at 433 MHz for real-time data transmission to a Ground Control Station (GCS Mission planner) and a Holybro M10 GNSS module for positioning. A Raspberry Pi 4B microcomputer communicates with the flight controller serially by sending flight commands in a python script via the Pymavlink library and handles data logging from the triaxial 5G sensor. The flightcontroller rotates the BLDC motors by sending a PWM value towards the Electronic Speed Controllers (ESCs). [Figure 2-2](#) provides an overview of all integrated hardware components.

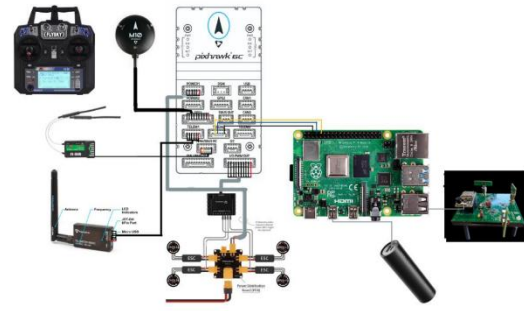


Figure 2-2: All onboard-electronics communicating with the Pixhawk 6C flightcontroller

The flight controller's Inertial Measurement Unit (IMU) underwent a temperature calibration procedure to minimize initialization time and improve the accuracy of gyroscope and accelerometer readings across a broad temperature range, thereby enhancing flight stability and control performance. The radio control (RC) system was calibrated to determine the minimum and maximum pulse-width modulation (PWM) values corresponding to the full range of the transmitter stick inputs. Magnetic compass calibration was performed using MAGfit, effectively reducing magnetic offsets and improving heading accuracy. A notch filter was applied to the flight controller to eliminate harmonic vibrations and associated noise in the sensor data. Finally, a Vertical Take-Off and Landing (VTOL) QuickTune procedure was executed to optimize the proportional (P), integral (I), and derivative (D) control gains for yaw, pitch, and roll dynamics, ensuring responsive and stable flight behavior.

B. Onboard electronic electromagnetic interference experiments

Two measurement campaigns are conducted to evaluate the impact of the onboard electronics (the BLDC motors, ESCs, telemetry radio (433 MHz), RC receiver (2.4 GHz) and Raspberry Pi) on the RF-EMF exposure measurements. Each component is activated individually to assess its individual effect on the received power P_r recorded by the triaxial 5G sensor.

Measurements are repeated with the sensor mounted in two orientations: upward (antennas facing the LiPo battery) and downward (antennas facing the ground), to determine the configuration that minimizes interference. The average power levels per axis ($P_{x,avg}$, $P_{y,avg}$ and $P_{z,avg}$) are computed

over 30 seconds of data acquisition, with a sampling rate of 25,000 samples per second.

C. Shielding experiments

To quantify the shielding effect of the drone's mechanical structure on RF-EMF measurements, controlled experiments are conducted in a semi-anechoic chamber. Continuous wave signals at 3.455, 3.530, 3.650, and 3.750 GHz, with transmission powers of 15 dBm and 18 dBm, are emitted from a TX antenna positioned at a height of 1.84 m toward the drone mounted at a height of 0.84 m on a rotating turntable, with a separation distance of 1.5 m. The received power P_r is recorded while the drone rotated at $2^\circ/\text{s}$ for two full 360° rotations. The procedure is repeated with only the 5G sensor not mounted on the drone, enabling a direct comparison. The shielding effect is derived by isolating the attenuation introduced by structural elements such as motor arms and propellers. Figure 2-3 shows the measurement setup.

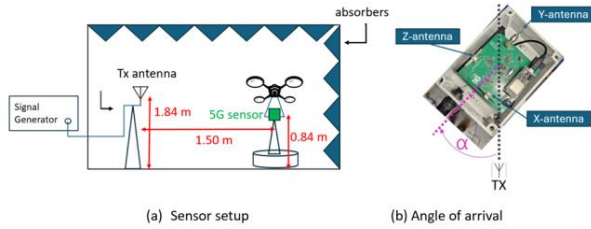


Figure 2-3: The triaxial 5G sensor is mounted on the drone and positioned on a motorized turntable at a height of 0.84 m, located 1.5m from the TX antenna. The TX antenna is fixed on a tripod at a height of 1.84 m. To isolate the influence of the drone structure, the same set of eight experiments is repeated with the 5G sensor alone, placed in the identical position and orientation. (a) α indicates the angle of incident power, which is the relative orientation between the sensor and the TX antenna.

D. Free-space calibration

In order to define the Antenna Factor (AF) of the 5G NR sensor mounted on the drone at frequencies 3.455, 3.530, 3.650, and 3.750 GHz, a free-space calibration is performed using a calibrated field strength analyzer (Narda SRM-3006) positioned identically to the drone's position in the shielding experiments as shown in Figure 2-3. The SRM-3006 records time-averaged electric field strength E_{avg} during two full 360° rotations. These reference values enable the determination of the sensor's frequency-dependent AF, allowing accurate conversion of received power to electric field strength for reliable RF-EMF exposure assessment.

E. In situ measurement setup

Figure 2-4 shows the *in situ* measurement campaign, which involved an autonomous drone flight along 16 predefined waypoints with a 10-second hover at each waypoint. A signal generator with a TX antenna is located at a lateral distance of 6.10 m from the vertical grid and emits a signal with a frequency of 3.530 GHz and an attenuation of 18 dBm. At each waypoint, the total received power P_{tot} is calculated as the root sum of squares (RSS) of $P_{x,avg}$, $P_{y,avg}$ and $P_{z,avg}$ using equation 1. This is converted to total power density S_{tot} using the AF at 3.530 GHz and equation 2. Lastly it's converted to total electric field strength E_{tot} by multiplying S_{tot} with Z_0 , the intrinsic impedance of free space using equation 3.

$$P_{tot} = \sqrt{\left(\frac{1}{n} \sum_{i=1}^n P_{x,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{y,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{z,i}\right)^2} \quad (1)$$

$$S_{tot} = \frac{P_{tot}}{AF} \quad (2)$$

$$E_{tot} = \sqrt{S_{tot} \cdot Z_0} \quad (3)$$

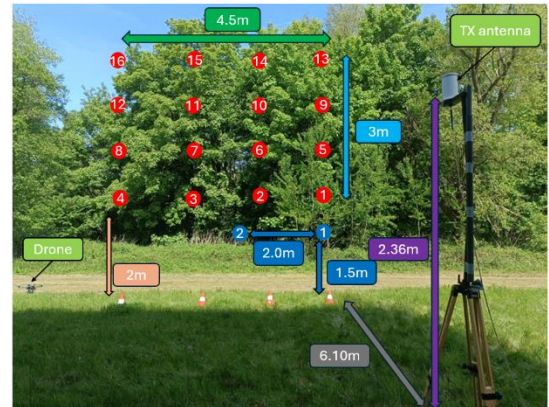


Figure 2-4: The red markers in the figure indicate the 16 predefined drone waypoints, which form a structured vertical measurement grid. Each waypoint is spaced 1.5 m apart horizontally, starting at a height of 2.0 m. Successive rows in the vertical direction are offset by 1.0 m, resulting in a three-dimensional grid covering a total area of 13.5 m^2 . These points represent the positions at which RF-EMF measurements were collected by the drone. The two blue markers indicate the locations of broadband electric field measurements performed with the Narda NBM-550 field strength meter. The TX antenna was positioned at a lateral distance of 6.10 m from the waypoint grid and mounted at a height of 2.36 m above ground level.

3. Results

A. Onboard electronic electromagnetic interference experiments results

Two measurement campaigns were conducted, with the triaxial 5G sensor facing upward and downward, as shown in [Figure 3-1](#). Interference from electronic components like the BLDC motors, ESC's and the telemetry radio (433MHz) was not measurable with received power P_r staying at the noise level of $P_x = -55.72$ dBm, $P_y = -57.73$ dBm and $P_z = -62.73$ dBm. The RC connection (2.4 GHz) does impact received power. When the RC receiver's antennas were mounted upward (antennas pointing straight up at 90° as illustrated in [Figure 3-2](#)) with the triaxial 5G sensor pointing up ([Figure 3-1](#)), the interference was minimized. For this optimal measurement configuration, a revised noise floor was defined by determining the average total, including all three axes, received power $P_{r,avg}$ for five 30-seconds exposure measurements. This established a revised noise floor of -53.59 dBm. This noise floor is defined as the total received power below which exposure measurements are no longer considered reliable due to potential interference from the RC. The optimal measurement configuration was adopted for subsequent experiments to minimize the impact of onboard electronics on RF-EMF measurements.

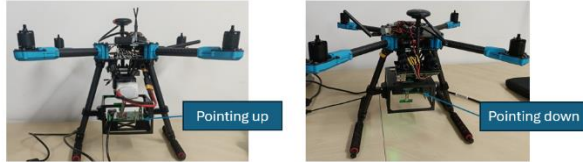


Figure 3-1: Measurement setup campaign 1: 5G sensor pointing up and measurement setup campaign 2: 5G sensor pointing down

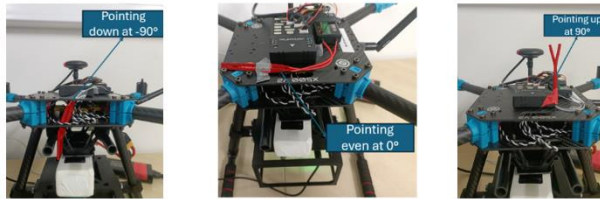


Figure 3-2: The RC IA6B receiver's antennas pointing down at -90° (a), pointing even at 0° (b) and pointing up at 90°

B. Shielding experiments results

To quantify the results from the shielding experiments a shielding percentage SP_{axis} was defined as function of the incident power angle α .

$$SP_{axis}(\alpha) = \frac{P_{r,drone+sensor}(\alpha) - P_{r,sensor}(\alpha)}{P_{r,sensor}(\alpha)} \cdot 100\% \quad (4)$$

Where:

- $P_{r,drone+sensor}(\alpha)$ is the received power by the 5G sensor on the drone at angle α [W]
- $P_{r,sensor}(\alpha)$ is the received power by the standalone 5G sensor at angle α [W]
- $SP_{axis}(\alpha)$ is the shielding factor at angle α [%]

The mean SP_{axis} is defined as the average shielding percentage across a full 360° clockwise and 360° counterclockwise rotation. The total mean shielding percentage SP_{total} is defined as the average SP_{axis} across the three axes for a specific frequency and attenuation.

$$\overline{SP_{total}} = \frac{1}{3}(\overline{SP_x} + \overline{SP_y} + \overline{SP_z}) \quad (5)$$

The shielding experiments demonstrated a frequency- and axis-dependent attenuation caused by the drone's mechanical structure. The average total shielding percentage SP_{total} across all frequencies (3.455, 3.530, 3.650, and 3.750 GHz) and attenuation levels (15 dBm and 18 dBm) was -7.07%, with the Z-axis experiencing the highest average attenuation of 11.69%. This is likely due to the Z-axis antenna's proximity to the landing gear pole and other structural components. Higher transmission powers (18 dBm) led to slightly higher shielding percentages, suggesting greater electromagnetic interaction with the drone's structure at stronger incident field strengths. [Figure 3-3](#) shows SP_{axis} in function of α for a frequency of 3.750 GHz and 13.26 dBm (15dBm minus 1.74 dBm cable loss). For the x-axis, the highest signal attenuation occurred near the lower left motor arm. The upper left and lower right motor arms created the second and third largest causes of shielding. For the y-axis the upper right, lower right and lower left motor arms are the major sources of shielding. For the Z-axis, the signal was predominantly attenuated across nearly all rotation angles except in sector between 259° - 283° .

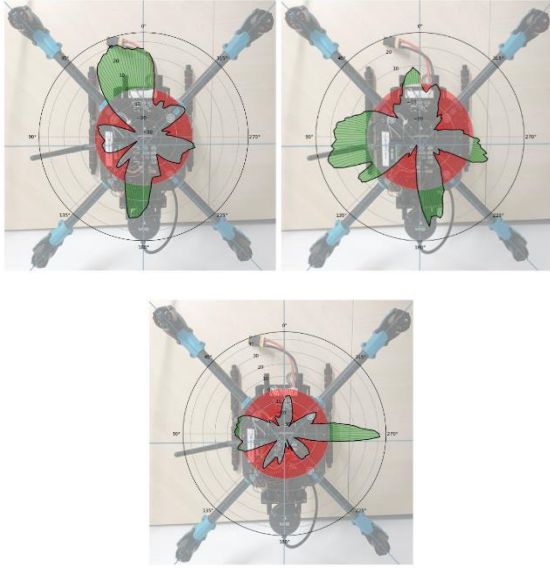


Figure 3-3: Shielding percentage SP for $f=3.750\text{GHz}$ and $\text{Att} = 13.26\text{ dBm}$ for the x-axis, y-axis and z-axis. The red coloured area represents the area where $\text{SP}_{\text{axis}} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area

C. Free-space calibration

The free-space calibration results showed a frequency-dependent AF ranging from 408.70 1/mm^2 at 3.530 GHz and 115.60 1/mm^2 at 3.750 GHz for 15 dBm as shown in Figure 3-4, with the sensor being most sensitive at 3.750 GHz . These AF values enabled accurate conversion of received power into electric field strength, ensuring reliable exposure assessment during *in situ* drone measurements.

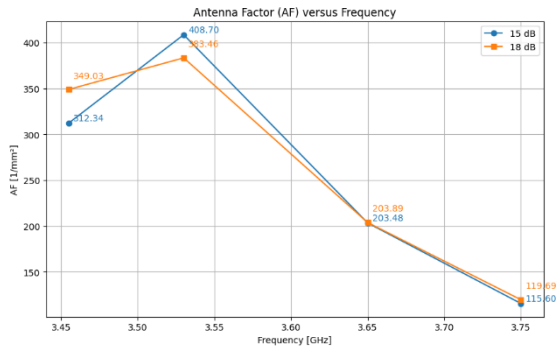


Figure 3-4: AF in function of the four frequencies 3.455 , 3.530 , 3.650 and 3.750 GHz

D. In situ measurement results

During the *in situ* measurement campaign, the autonomous drone executed a flight along 16 predefined waypoints arranged in a structured vertical 2D grid. At each waypoint, the triaxial 5G sensor measured received power along all three axes, which was then converted into total electric field strength using equations 1, 2 and 3 and the

previously determined frequency-dependent AF of 383.46 1/mm^2 for the frequency of 3.530 GHz at 18 dBm attenuation from the TX antenna. The measured electric field strength values exhibited clear spatial variation, with peak values ranging from 3.83 V/m during the first flight (Figure 3-5) to 4.25 V/m during the second flight (Figure 3-6) observed near the transmitting antenna. These results were visualized through heat maps that highlight the spatial distribution of RF-EMF exposure. To interpolate field strength between discrete measurement points, exponential Kriging was applied, accounting for spatial autocorrelation in the data. Although the drone's GPS module (Holybro M10) introduced a circular error probable (CEP) of approximately 2 meters which made the waypoints drift in between separate flights, the positional deviations remained within acceptable bounds for exposure mapping.

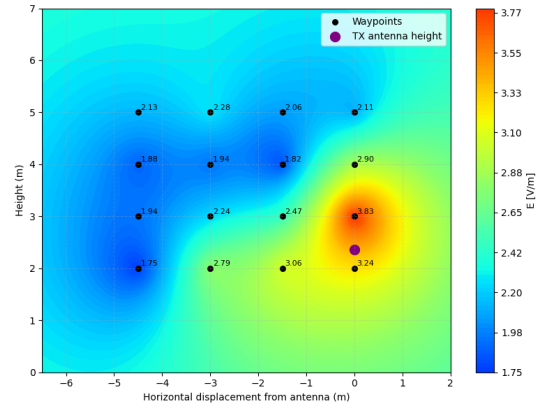


Figure 3-5: Interpolated field of E_{avg} using exponential kriging during the first flight. The vertical grid is constructed left of the TX antenna, which location is marked by the purple dot on the heat map. The location of maximum RF-EMF exposure coincides with the position of the TX antenna, specifically between waypoints 1 and 5.

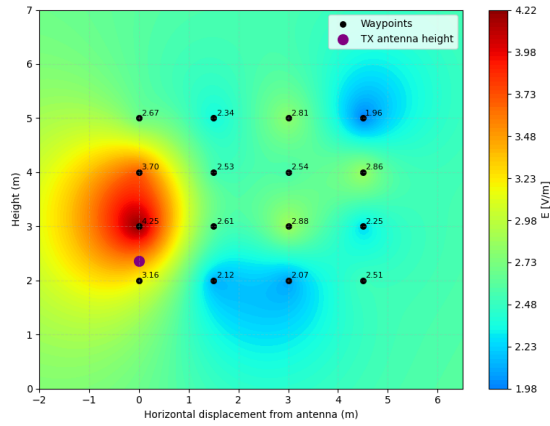


Figure 3-6: Interpolated field of E_{avg} using exponential kriging during the second flight. The vertical grid is constructed to the right of the TX antenna. The location of maximum RF-EMF exposure coincides with the position of the TX antenna, specifically between waypoints 4 and 8.

4. Conclusion and further perspectives

The *in situ* campaign demonstrated the feasibility and accuracy of using an autonomous drone system for high-resolution three-dimensional RF-EMF exposure assessment in the n78 frequency band. A robust drone platform was developed and thoroughly calibrated to ensure flight stability and sensor accuracy. Through onboard interference and shielding experiments, key system design decisions were validated, minimizing electronic noise and structural attenuation. The frequency-dependent AF was experimentally determined, enabling reliable conversion of received power into electric field strength. During the *in situ* campaign, the drone autonomously mapped spatial variations in exposure near a signal generator with a TX antenna, with peak electric fields ranging from 3.83 V/m to 4.25 V/m. These results confirm that autonomous aerial measurements can provide high-resolution, reproducible data for 5G exposure monitoring.

Future work should focus on improving positional accuracy through integration of Real-Time Kinematic (RTK) GPS or ultra-wideband (UWB) systems. Additionally, equipping the drone with a depth camera could enable safe close-range measurements near 5G base station antennas. Expanding the measurement system to support higher frequencies such as millimeter-wave (mmWave) bands would further increase the applicability of the platform in future 5G and 6G networks.

5. References

- [1] International Commission on Non-Ionizing Radiation Protection (ICNIRP), “Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz),” *Health Phys.*, vol. 118, no. 5, pp. 483–524, 2020.
- [2] J. Van der Straeten, et al., “Design and validation of a low-cost triaxial 5G RF-EMF exposure sensor,” presented at the IEEE Conf., Ghent, Belgium, 2024.

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1. Introductie

De wereldwijde uitrol van 5G New Radio (NR) vereist een efficiënte monitoring van blootstelling aan elektromagnetische velden in het radiofrequentiebereik (RF-EMV). Bezorgdheid over mogelijke biologische effecten op de volksgezondheid vraagt om nauwkeurige gegevens om naleving van blootstellingsrichtlijnen, zoals die opgesteld door de ICNIRP, te waarborgen. RF-EMV-meetmethoden, zoals handmatig scannen met draagbare exposimeters, zijn arbeidsintensief en beperkt in het vastleggen van driedimensionale ruimtelijke variaties van het elektrisch veld nabij 5G basisstation-antennes op grote hoogte.

Het primaire doel van deze scriptie is het ontwikkelen van een autonome quadcopter geïntegreerd met een triaxiale 5G-sensor, met als doel de efficiëntie en consistentie van 5G NR RF-EMV-blootstellingsmetingen te verbeteren via een kosteneffectieve benadering. Het secundaire doel betreft de inzet van dit autonome systeem tijdens een *in-situ* meetcampagne nabij een 5G-basisstation. Tijdens deze campagne wordt een verticaal 2D-raster met meerdere meetpunten ontwikkeld om de RF-EMV-blootstelling te karakteriseren, waarbij zowel de gemiddelde (E_{avg}) als de maximale (E_{max}) elektrische veldsterkten worden gemeten en gevisualiseerd via heatmaps. Deze metingen worden verzameld via een volledig geautomatiseerd vluchtsript geschreven in Python, waarmee de drone systematisch blootstellingsgegevens vastlegt op vooraf gedefinieerde posities binnen het raster. De studie onderzoekt ook mogelijke interferentie door de boardelektronica van de drone en het afschermende effect van zijn mechanische structuur op de meetnauwkeurigheid van de 5G sensor.

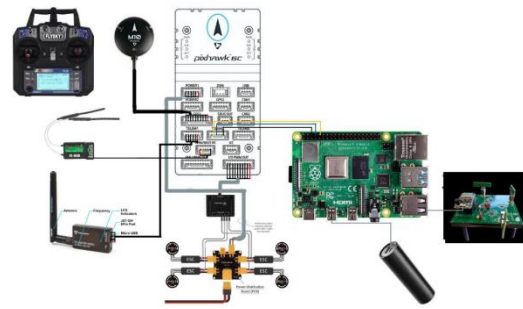
Door zich te richten op de n78-frequentieband, die veel wordt ingezet voor 5G-diensten in België, levert dit onderzoek een bijdrage aan meer transparantie in de monitoring van de volksgezondheid en biedt het waardevolle gegevens voor epidemiologische studies.

De literatuurstudie identificeerde de n78-frequentieband (3,4–3,8 GHz) als cruciaal voor de commerciële uitrol van 5G NR in België. Analyse van 5G NR-technologieën, waaronder Massive MIMO, Orthogonal Frequency Division Multiplexing (OFDM) en beamforming, toonde hun aanzienlijke impact op RF-distributie en ruimtelijke variabiliteit aan. De huidige wetenschappelijke inzichten over RF-EMV-blootstelling wijzen op mogelijke biologische effecten. Daarom heeft de ICNIRP in 2020 haar gestandaardiseerde blootstellingsrichtlijnen geactualiseerd, waarbij een referentieniveau van 61,7 V/m voor blootstelling voor de algemene bevolking werd vastgesteld [1].

Om RF-EMV-blootstelling nauwkeurig te meten, werden verschillende sensortechnologieën bestudeerd. Er werd bijzondere aandacht besteed aan hardware-gebaseerde en frequentieselectieve triaxiale sensoren die in staat zijn om in real-time elektrische veldsterkte te meten. Deze werden vergeleken met andere oplossingen zoals Software-Defined Radios (SDRs) op vlak van software en frequentiespectrum. Van der Straeten et al. ontwikkelde een frequentieselectieve, laaggeprijsde triaxiale 5G RF-EMV-sensor die in staat is blootstelling veroorzaakt door 5G-communicatie te meten in de n78 (3300–3800 MHz) en de n77 (3300–4200 MHz) frequentieband tot 3900 MHz [2].

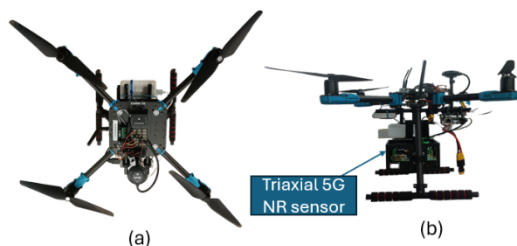
In het kader van deze scriptie werden drone-gebaseerde meetprotocollen en systeem-

overzicht van alle geïntegreerde hardwarecomponenten.



2. Materialen en methodes

Om RF-EMV-blootstelling in de n78-band (3,4– 3,8 GHz) te evalueren, werd een autonome quadcopter ontwikkeld en uitgerust met een frequentie- selectieve triaxiale 5G NR-sensor, ontwikkeld door Van der Straeten et al [3]. De drone werd geselecteerd na vergelijking van drie systemen: een Arduino-gebaseerde drone, een DJI S1000 octocopter en de Holybro X500 V2 Pixhawk drone. De Holybro X500 V2 werd uiteindelijk gekozen vanwege zijn balans tussen modulariteit, kost en prestaties. [Figuur 2-1a](#) toont de Holybro X500 V2 in bovenaanzicht en [Figuur 2-1b](#) toont de hoe de triaxiale 5G NR sensor geassembleerd is op de drone.



De Inertial Measurement Unit (IMU) van de flightcontroller onderging een temperatuurkalibratieprocedure om de initialisatietijd te minimaliseren en de nauwkeurigheid van gyroscoop- en versnellingsmetermetingen over een breed temperatuurbereik te verbeteren, waardoor de vluchtstabiliteit en stuurprestaties werden versterkt. Het radiobesturingssysteem (RC) werd gekalibreerd om de minimale en maximale pulse-width modulation (PWM)-waarden te bepalen die overeenkomen met het volledige bereik van de stickbewegingen van de transmitter. Het magnetische kompas werd gekalibreerd met behulp van de MAGfit calibratie, waarmee magnetische offsets effectief werden gereduceerd en de nauwkeurigheid van de koersbepaling werd verbeterd. Een notch-filter werd toegepast op de flightcontroller om harmonische trillingen en gerelateerde ruis in de sensordata te elimineren. Tot slot werd een Vertical Take-Off and Landing (VTOL) QuickTune-procedure uitgevoerd om de PID regelparameters voor yaw-, pitch- en rollbewegingen te optimaliseren, met als doel een responsief en stabiel vlieggedrag te waarborgen.

De drone werd uitgerust met een Pixhawk 6C flightcontroller. De communicatie met de flightcontroller verloopt via verschillende apparaten: een FlySky FS-i6 RC-zender en FS-IA6B-ontvanger (2,4 GHz), een telemetrie radio (433 MHz), een Holybro M10 GPS en een Raspberry Pi 4B. Deze laatste communiceert met de flightcontroller via Python commando's afkomstig uit de Pymavlink library, stuurt vluchtcommando's aan en slaat gegevens van de triaxiale 5G-sensor op. De flightcontroller laat de BLDC motoren roteren door een PWM waarde richting de electronic speed controllers (ESCs) te sturen. [Figuur 2-2](#) geeft een

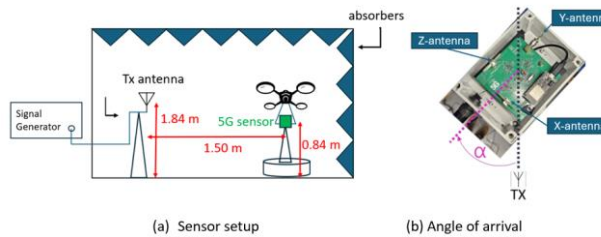
Twee meetcampagnes werden uitgevoerd om de invloed van de boordelektronica (de BLDC-motoren, ESCs, telemetrieradio (433 MHz), RC-ontvanger (2,4 GHz) en Raspberry Pi) op de RF-EMV-blootstellingsmetingen te evalueren. Elk onderdeel werd afzonderlijk en in combinatie geactiveerd om het individuele effect op het ontvangen vermogen P_r , geregistreerd door de triaxiale 5G-sensor, te beoordelen.

De metingen werden herhaald met de sensor gemonteerd in twee oriëntaties: omhoog (antennes

gericht naar de LiPo-batterij) en omlaag (antennes gericht naar de grond), om de configuratie te bepalen die de interferentie minimaliseert. De gemiddelde vermogensniveaus per as ($P_{x,avg}$, $P_{y,avg}$ en $P_{z,avg}$) werden berekend over een gegevens-opname van 30 seconden, met een bemonsteringsfrequentie van 25.000 metingen per seconde.

C. Afschermingsexperimenten

Om het afschermingseffect van de mechanische structuur van de drone op RF-EMV-metingen te kwantificeren, werden gecontroleerde experimenten uitgevoerd in een semi-anechoïsche kamer. Continue golfsignalen bij 3.455, 3.530, 3.650 en 3.750 GHz, met zendvermogens van 15 dBm en 18 dBm, werden uitgezonden vanaf een TX-antenne die op een hoogte van 1,84 m was geplaatst, gericht op de drone die op een hoogte van 0,84 m stond gemonteerd op een roterende draaitafel, met een onderlinge afstand van 1,5 m. Het ontvangen vermogen P_r werd geregistreerd terwijl de drone roteerde aan $2^\circ/s$ tijdens twee volledige 360° -rotaties. De procedure werd herhaald met enkel de 5G-sensor, niet gemonteerd op de drone, waardoor een directe vergelijking mogelijk was. Het afschermingseffect werd afgeleid door de verzwakking te isoleren die werd veroorzaakt door structurele elementen zoals motorarmen en propellers. [Figuur 2-3](#) toont de meetopstelling.



Figuur 2-3: De triaxiale 5G-sensor is gemonteerd op de drone en geplaatst op een gemotoriseerde draaitafel op een hoogte van 0,84 m, op een afstand van 1,5 m van de TX-antenne. De TX-antenne is bevestigd op een statief op een hoogte van 1,84 m. Om de invloed van de dronestructuur te isoleren, wordt dezelfde reeks van acht experimenten herhaald met enkel de 5G-sensor, geplaatst in exact dezelfde positie en oriëntatie. (a) De invalshoek α geeft de relatieve oriëntatie aan tussen de sensor en de zender. (b) door het verschil tussen beide situaties te berekenen als functie van de invalshoek.

D. Anechoïsche calibratie

Om de antennefactor (AF) van de op de drone gemonteerde 5G NR-sensor te bepalen bij frequenties van 3.455, 3.530, 3.650 en 3.750 GHz, werd een vrije ruimte kalibratie uitgevoerd met behulp van een gekalibreerde veldsterktemeter (Narda SRM-3006), die identiek gepositioneerd werd op de locatie van de drone in de afschermingsexperimenten, zoals weergegeven in [Figuur 3](#). De SRM-3006 registreerde de tijdsgemiddelde elektrische veldsterkte E_{avg} tijdens twee volledige 360° -rotaties. Deze referentiewaarden maakten het mogelijk om de frequentieafhankelijke AF van de sensor te bepalen, waardoor een nauwkeurige omzetting van ontvangen vermogen naar elektrische veldsterkte mogelijk werd voor betrouwbare RF-EMV-blootstellingsbeoordelingen.

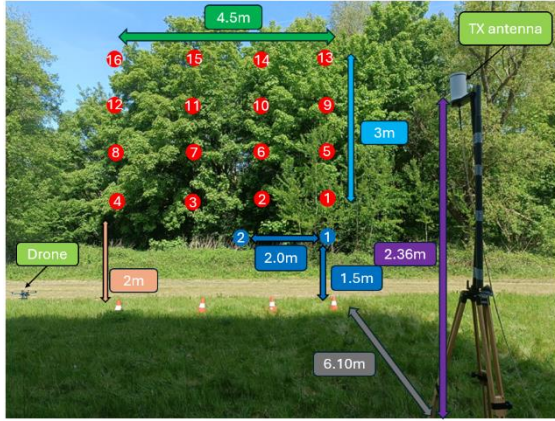
E. In situ meetopstelling

[Figuur 2-4](#) toont de *in situ* meetcampagne, waar de drone autonoom in 16 vooraf bepaalde waypoints van een 2D verticaal meetraster metingen neemt. Een signaalgenerator met een TX antenne op is gelokaliseerd op een loodrechte afstand van 6.10 m van het verticale raster and stuur een signaal uit met een frequentie van 3.530 GHz met een zendvermogen van 18 dBm. In elk waypoint werd 10 seconden gemeten door de drone ter plaatse te laten hoveren. Het totaal-vermogen P_{tot} werd berekend via RSS van $P_{x,avg}$, $P_{y,avg}$ en $P_{z,avg}$ aan de hand van vergelijking 1. Vervolgens werd P_{tot} omgezet naar vermogens-dichtheid S_{tot} via de antennefactor (bij 3,530 GHz) met vergelijking 2. Ten slotte wordt de totale veldsterkte E_{tot} bepaald door vermenigvuldiging van S_{tot} met de vrije ruimte impedantie Z_0 via vergelijking 3.

$$P_{tot} = \sqrt{\left(\frac{1}{n} \sum_{i=1}^n P_{x,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{y,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{z,i}\right)^2} \quad (1)$$

$$S_{tot} = \frac{P_{tot}}{AF} \quad (2)$$

$$E_{tot} = \sqrt{S_{tot} \cdot Z_0} \quad (3)$$



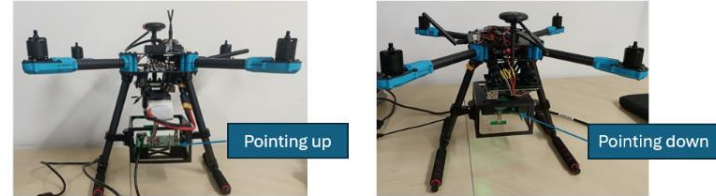
Figuur 2-4: De rode markeringen in de figuur geven de 16 vooraf bepaalde drone-waypoints aan, die samen een gestructureerd verticaal meetraster vormen. Elk waypoint ligt 1.5 m uit elkaar in horizontale richting, beginnend op een hoogte van 2.0 m. Opeenvolgende rijen in verticale richting zijn verschoven met 1.0 m, wat resulteert in een driedimensionaal rooster met een totale oppervlakte van 13.5 m². Deze punten vertegenwoordigen de locaties waarop RF-EMV-metingen door de drone zijn uitgevoerd. De twee blauwe markeringen geven de locaties aan waar breedbandige elektrische veldmetingen zijn uitgevoerd met de Narda NBM-550 veldsterktemeter. De TX-antenne was geplaatst op een zijdelingse afstand van 6.10 m van het raster en gemonteerd op een hoogte van 2.36 m boven het maaiveld.

3. Resultaten

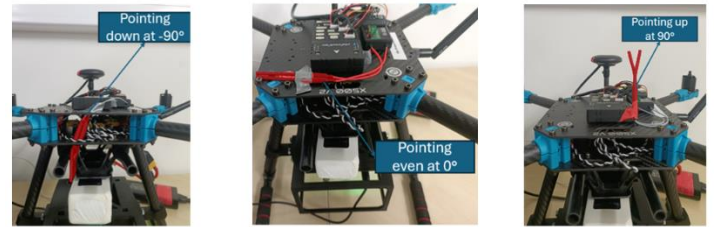
A. Elektromagnetische interferentie door boardelektronica resultaten

Twee meetcampagnes werden uitgevoerd met de triaxiale 5G-sensor respectievelijk naar boven en naar beneden gericht, zoals weergegeven in [Figuur 3-1](#). Interferentie van elektronische componenten zoals de BLDC-motoren, ESCs en de telemetrieradio (433 MHz) was niet meetbaar, het ontvangen vermogen P_r bleef op ruisniveau, namelijk $P_x = -55.72$ dBm, $P_y = -57.73$ dBm en $P_z = -62.73$ dBm. De RC-verbinding (2,4 GHz) beïnvloedt echter het ontvangen vermogen P_r . Wanneer de antennes van de RC-ontvanger omhoog waren gemonteerd (antennes recht omhoog gericht onder een hoek van 90°, zoals geïllustreerd in [Figuur 3-2](#)) en de triaxiale 5G-sensor eveneens omhoog wees ([Figuur 3-1](#)), werd de interferentie geminimaliseerd. Voor deze optimale meetconfiguratie werd een herziene ruisvloer gedefinieerd door het gemiddelde van het totale, over alle drie de assen, ontvangen vermogen $P_{r,avg}$ te bepalen op basis van vijf blootstellingsmetingen van elk 30 seconden. Dit resulteerde in een herziene ruisvloer van -53,59 dBm. Deze ruisvloer wordt gedefinieerd als het totale gemiddelde ontvangen vermogen waaronder

blootstellingsmetingen niet langer als betrouwbaar worden beschouwd vanwege mogelijke interferentie door de RC. Deze configuratie werd dan ook toegepast in de daaropvolgende experimenten om de invloed van de boardelektronica op RF-EMV-metingen te minimaliseren.



Figuur 3-1: Metingscampagne 1: 5G sensor gericht naar boven Metingscampagne 2: 5G sensor gericht naar onder



Figuur 3-2: De antennes van de RC 1A6B-ontvanger gericht naar beneden onder -90° (a), horizontaal gericht op 0° (b) en naar boven gericht op 90°

B. Afschermingsexperimenten resultaten

Om de resultaten van de afschermingsexperimenten te kwantificeren, werd een afschermingspercentage SP_{axis} gedefinieerd als functie van de invalshoek α van het inkomende signaal, berekend zoals in vergelijking 4.

$$SP_{axis}(\alpha) = \frac{P_{r,drone+sensor}(\alpha) - P_{r,sensor}(\alpha)}{P_{r,sensor}(\alpha)} \cdot 100\% \quad (4)$$

Waar:

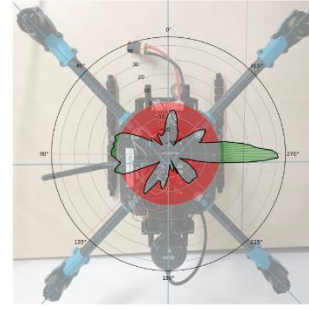
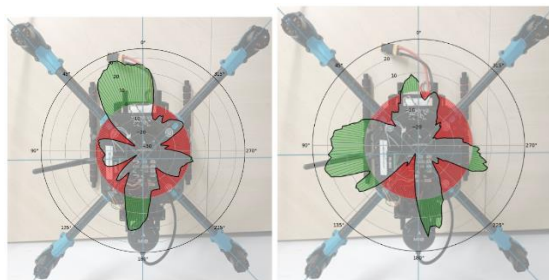
- $P_{r,drone+sensor}(\alpha)$ is het ontvangen vermogen van de 5G sensor geassembleerd op de drone op hoek α [W]
- $P_{r,sensor}(\alpha)$ is het ontvangen vermogen van uitsluitend de 5G sensor op hoek α [W]
- $SP_{axis}(\alpha)$ is het afschermingspercentage bij hoek α [%]

Het gemiddelde afschermingspercentage SP_{axis} is gedefinieerd als het gemiddelde afschermingspercentage over een volledige 360° rotatie in wijzerzin en een volledige 360° rotatie

tegenwijzerzin. Het totale gemiddelde afschermingspercentage SP_{total} wordt gedefinieerd als het gemiddelde van SP_{axis} over de drie assen voor een specifieke combinatie van frequentie en zendvermogen (bijv. 3.455 GHz en 15 dBm), zoals in vergelijking 5.

$$\overline{SP_{total}} = \frac{1}{3}(\overline{SP_x} + \overline{SP_y} + \overline{SP_z})(5)$$

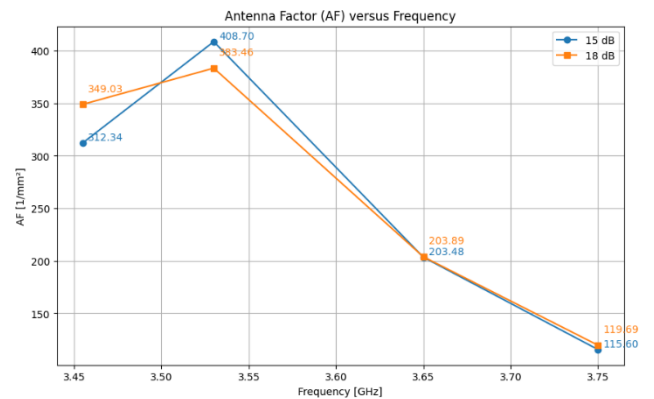
De afschermingsexperimenten demonstreerden een frequentie- en as-gevoelige demping veroorzaakt door de drone's mechanische structuur. Het gemiddelde totale afschermingspercentage SP_{total} over alle frequenties (3.455, 3.530, 3.650 en 3.750 GHz) en vermogensniveaus (15 dBm en 18 dBm) bedroeg -7,07%, waarbij de Z-as de hoogste gemiddelde verzwakking ondervond van 11,69%. Dit is waarschijnlijk te wijten aan de nabijheid van de Z-as antenne tot het landingsgestel en andere structurele componenten. Hogere zendvermogens (18 dBm) leidden tot iets hogere afschermingspercentages, wat wijst op een sterkere elektromagnetische interactie met de dronestructuur bij hogere veldsterktes. [Figuur 3-3](#) toont SP_{axis} als functie van α voor een frequentie van 3.750 GHz en 13,26 dBm (15 dBm minus 1,74 dBm kabelverlies). Voor de x-as, trad de grootste signaalverzwakking op nabij de linker onderste motorarm. De linker bovenste en rechter onderste motorarmen veroorzaakten de tweede en derde grootste afscherming. Voor de y-as waren de rechter bovenste, rechter onderste en linker onderste motorarmen de voornaamste bronnen van afscherming. Voor de Z-as werd het signaal over bijna alle rotatiehoeken verzwakt, behalve in de sector tussen 259° en 283°.



Figuur 3-3: Afschermingspercentage SP_{axis} voor $f = 3.750\text{GHz}$ en $Att = 13.26\text{ dBm}$ voor de x-as, y-as en z-as. Het roodgekleurde gebied vertegenwoordigt het gebied waar $SP_{axis} \leq 0\%$. In dit gebied verzwakt de drone het invallende vermogenssignaal effectief. Het groen gekleurde gebied vertegenwoordigt het gebied waar $SP_{axis} \geq 0\%$. In dit gebied versterkt de drone het invallende vermogenssignaal effectief.

C. Anechoïsche calibratie resultaten

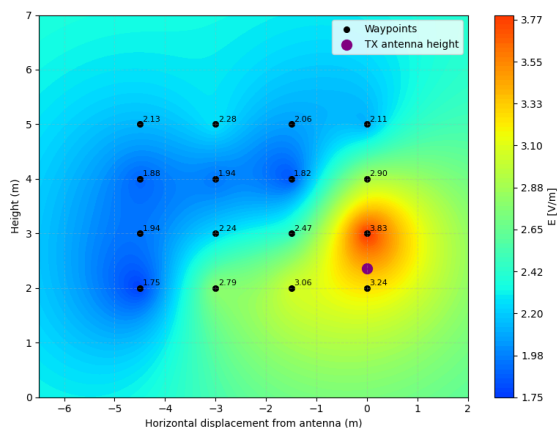
De resultaten van de anechoïsche kalibratie toonden een frequentie-afhankelijke AF zoals getoond in [Figuur 3-4](#), variërend van 408,70 1/mm² bij 3,530 GHz tot 115,60 1/mm² bij 3,750 GHz voor 15 dBm, waarbij de sensor het meest gevoelig was bij 3,750 GHz. [Figuur 8](#) toont het verloop van AF i.f.v. de frequentie. Deze AF-waarden maakten een nauwkeurige omzetting van ontvangen vermogen naar elektrische veldsterkte mogelijk, wat zorgde voor een betrouwbare blootstellingsbeoordeling tijdens de in-situ dronemetingen.



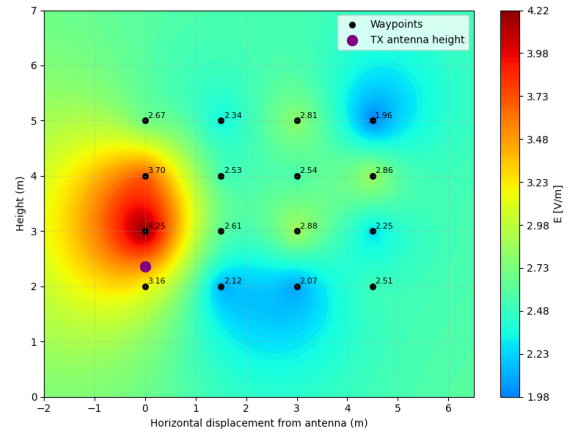
Figuur 3-4: AF in functie van de vier centrumfrequenties 3.455, 3.530, 3.650 en 3.750 GHz

D. In situ metingsresultaten

Tijdens de *in-situ* meetcampagne voerde de autonome drone een vlucht uit langs 16 vooraf gedefinieerde waypoints die waren opgesteld in een gestructureerd verticaal 2D-raster. Op elk waypoint mat de triaxiale 5G-sensor het ontvangen vermogen langs alle drie de assen, dat vervolgens werd omgerekend naar totale elektrische veldsterkte met behulp van vergelijkingen 1, 2 en 3 en de eerder bepaalde frequentie-afhankelijke AF van $383,46 \text{ 1/mm}^2$ voor de frequentie van $3,530 \text{ GHz}$ bij een zendvermogen van 18 dBm vanaf de TX-antenne. De gemeten elektrische veldsterkte vertoonde duidelijke ruimtelijke variatie, met piekwaarden die varieerden van $3,83 \text{ V/m}$ tijdens de eerste vlucht (Figuur 3-5) tot $4,25 \text{ V/m}$ tijdens de tweede vlucht (Figuur 3-6), waargenomen in de buurt van de zendende antenne. Deze resultaten werden gevisualiseerd aan de hand van heatmaps die de ruimtelijke verspreiding van RF-EMV-blootstelling benadrukken. Om veldsterkte te interpoleren tussen discrete meetpunten, werd gebruik gemaakt van exponentiële Kriging, waarbij rekening werd gehouden met ruimtelijke autocorrelatie in de data. Hoewel de GPS-module van de drone (Holybro M10) een circular probable error (CEP) van ongeveer 2 meter introduceerde, waardoor waypoints tussen afzonderlijke vluchten licht versprongen, bleven de positionele afwijkingen binnen aanvaardbare marges voor blootstellingskaartanalyse.



Figuur 3-5: Geïnterpoleerde gemiddelde elektrische veldblootstelling E_{avg} aan de hand van exponentiële Kriging in de eerste vlucht. Het verticale raster is geconstrueerd aan de linkerkant van de TX antenne. De locatie waar de RF-EMV blootstelling maximaal werd, valt samen met de positie van de TX antenne, meer specifiek tussen waypoints 1 en 5.



Figuur 3-6: Geïnterpoleerde gemiddelde elektrische veldblootstelling E_{avg} aan de hand van exponentiële Kriging in de tweede vlucht. Het verticale raster is geconstrueerd aan de rechterkant van de TX antenne. De locatie waar de RF-EMV blootstelling maximaal werd, valt samen met de positie van de TX antenne, meer specifiek tussen waypoints 4 en 8.

4. Conclusies en toekomstperspectieven

De *in-situ* meetcampagne toonde de haalbaarheid en nauwkeurigheid aan van het gebruik van een autonoom dronesysteem voor driedimensionale RF-EMV-blootstellingsmetingen met hoge resolutie in de n78-frequentieband. Er werd een robuust droneplatform ontwikkeld en grondig gekalibreerd om vluchtstabiliteit en sensornauwkeurigheid te garanderen. Via experimenten rond boordinterferentie en afscherming werden belangrijke ontwerpkeuzes gevalideerd, waardoor elektronische ruis en structurele verzwakking tot een minimum werden beperkt. De frequentie-afhankelijke AF werd experimenteel bepaald, wat een betrouwbare omzetting van ontvangen vermogen naar elektrische veldsterkte mogelijk maakte. Tijdens de *in-situ* campagne bracht de drone autonoom ruimtelijke variaties in blootstelling nabij een signaalgenerator met een TX antenne in kaart, met piekveldsterktes van $3,83 \text{ V/m}$ tot $4,25 \text{ V/m}$. Deze resultaten bevestigen dat autonome metingen vanuit de lucht gedetailleerde en reproduceerbare gegevens kunnen leveren voor toezicht op 5G-blootstelling.

Toekomstig werk zou zich moeten richten op het verbeteren van de positionele nauwkeurigheid via integratie van Real-Time Kinematic (RTK) GPS of ultra-wideband (UWB)-systemen. Daarnaast zou het uitrusten van de drone met een dieptecamera veilige nabije metingen mogelijk maken in de buurt van zendantennes. Een uitbreiding van het meetsysteem naar hogere frequenties zoals

millimetergolven (mmWave) zou de toepasbaarheid van het platform in toekomstige 5G- en 6G-netwerken verder vergroten. focussen op positionele nauwkeurigheid (RTK-GPS of UWB), obstakeldetectie (dieptecamera), en uitbreiding naar mmWave-frequenties t.b.v. 6G-netwerken.

5. Referenties

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- [2] J. Van der Straeten, et al., *“Design and validation of a low-cost triaxial 5G RF-EMF exposure sensor,”* presented at the IEEE Conf., Ghent, Belgium, 2024.

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Abbreviations

Abbreviation	Meaning
3GPP	3rd Generation Partnership Project
5GC	5G Core Network
AF	Antenna Factor
AMF	Access and Mobility Management Function
AR	Augmented Reality
BIPT	Belgian Institute for Postal Services and Telecommunications
BLDC	Brushless DC
CAD	Computer-Aided Design
CEP	Circular Error Probable
CSI	Channel State Information
Eavg	Average Electric Field Strength
E _{max}	Maximum Electric Field Strength
E _{tot}	Total Electric Field Strength
eMBB	Enhanced Mobile Broadband
EKF3	Extended Kalman Filter 3
EME	Electromagnetic Environment
E _{min}	Minimum Electric Field
E _{max}	Maximum Electric-Field
EMI	Electromagnetic Interference
ESC	Electronic Speed Controller
GCS	Ground Control Station
GSCN	Global Synchronization Raster Channel
GNSS	Global Navigation Satellite System
gNB	gNodeB
ICNIRP	International Commission on Non-Ionizing Radiation
IEI-EMF	Idiopathic Environmental Intolerance to Electromagnetic Fields
IMU	Inertial Measurement Unit
IR	Infrared Radiation
IRPA	International Radiation Protection Association

LTE	Long-Term Evolution
MAGfit	Magnetometer Auto Gain Fit
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
mMTC	massive Machine-Type Communications
mmWave	Millimeter Wave
MRI	Magnetic Resonance Imaging
NFV	Network Functions Virtualization
NG-RAN	Next-Generation Radio Access Network
NRB	Number of Resource Blocks
OFDM	Orthogonal Frequency Division Multiplexing
PBCH	Physical Broadcast Channel
PDB	Power Distribution Board
PID	Proportional-Integral-Derivative
PLA	Polyactic Acid
PSS	Primary Synchronization Signal
PWM	Pulse Width Modulation
QoS	Quality of Service
RC	Radio Control
RF	Radio Frequency
RSS	Root Sum of Squares
RTK	Real-Time Kinematics
RF-EMF	Radio-Frequency Electromagnetic Field
SAR	Specific Absorption Rate
SBA	Service-Based Architecture
SBI	Service-Based Interface
SDR	Software-Defined Radio
SHF	Super High Frequency
SMF	Session Management Function
SNR	Signal-to-Noise Ratio
SP	Shielding Percentage

SRS	Sounding Reference Signals
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
SDN	Software-Defined Networking
SMA	SubMiniature version A
TX	Transmitting
UE	User Equipment
URLLC	Ultra-Reliable Low-Latency Communication
UAS	Unmanned Aircraft System
UPF	User Plane Function
UV	Ultraviolet Radiation light.
UWB	Ultra-Wideband
VR	Virtual Reality
VTOL	Vertical Take-Off and Landing
WHO	World Health Organization

Artificial intelligence

Throughout this thesis artificial intelligence in the form of Large Language Models (LLMs) were used in assistance for scientific writing, coding and finding scientific sources for the literature study. All information received from the LLMs was always analysed thoroughly and never copied without due diligence. A concise overview of the LLMs employed and their respective purposes follows:

ChatGPT (GPT-3.5, GPT-4.0):

- Help by debugging Python code in several parts of the data-analysis for the drone's onboard electronics interference and shielding experiments.
- Help by finding useful scientific sources for the literature study by providing links and highlighting relevant pages for the subject (e.g., RF-EMF, 5G NR, etc...) in the source.
- Help by rewriting manually written text to enhance fluidity, clarity and the scientific writing style.

Gemini (2.5 Flash) :

- Gemini 2.5 Flash is capable of using a “Deep Research” function, which uses more time to examine your prompt and it researches way more sources to prepare its answer to your prompt. This LLM was used to answer substantive questions about data processing in exponential Kriging and also advised me on certain strategies, which should be implemented during data processing for the shielding experiments.

Grok (Grok 3) :

- Grok has an advanced visual processing tool to create AI images and cartoons completely free-of-cost. This was used for example in [Figure 3-15](#) to draw a cartoon from the SRM 3006 Field Strength Analyzer.

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Summary

This thesis provides a detailed analysis on developing and integrating an autonomous quadcopter system for 5G radio-frequency electromagnetic field (RF-EMF) exposure measurements with its focus on the Super High Frequency (SHF) band (3–30 GHz) used by 5G New Radio (NR) in Belgium. The primary objective is to enhance the efficiency of RF-EMF exposure measurement near 5G base stations by quantifying significant parameters such as average electric field strength (E_{avg}), minimum electric field and maximum electric field (E_{max}) in the three-dimensional space, thereby reducing manual effort and improving data collection consistency.

The thesis begins with a comprehensive literature review of 5G NR technology, from its architecture (User Equipment, Next-Generation Radio Access Network, and 5G Core Network) to key physical layer technologies (e.g., Orthogonal Frequency Division Multiplexing, Massive MIMO, and beamforming) and network/application layer innovations (e.g., Software-Defined Networking, Network Function Virtualization, and network slicing). It also covers RF-EMF properties, biological effects, regulatory guidelines (e.g., ICNIRP), and measurement techniques, highlighting the advantages of drone-based assessment for spatial data collection.

The research process is comparative analysis of three drone platforms (Arduino, Holybro Pixhawk, and DJI S1000), and Holybro X500 V2 has been selected based on cost, modularity, and performance balance. A triaxial 5G NR sensor was placed on the drone, and strict calibration processes (e.g., IMU, accelerometer, radio, compass and notch filtering) were conducted to make measurements precise. The software design provided autonomous flight capabilities through a Python waypoint navigation system supplemented with a Mission Planner waypoint editor.

Experimental findings focused on three aspects: (1) onboard electronics interference, which was minimized by keeping the 5G sensor face-up, reducing interference by approximately 3 dB; (2) shielding effect of the drone, which was frequency- and axis-dependent, and the Z-axis was most attenuated (-7.07% on average for all three axes) owing to the blocking of structures; and (3) the Antenna Factor (AF), calculated to convert received power to electric field strength, with maximum sensitivity at 3.750 GHz. In situ measurements over a 16-waypoint grid showed spatial variations in E-field strength, with peak values of around 3.83–4.25 V/m closest to the transmitting antenna. Exponential kriging was employed for interpolation, accounting for spatial autocorrelation, though GPS errors (M10 GPS with a CEP 2.0 m) created small positional variations between flights.

The study determines that RF-EMF surveillance by drones is a viable, efficient method of 5G exposure assessment with flexibility and detailed spatial data. Future studies could involve GPS precision improvement and covering measurements up to higher frequency ranges (e.g., mmWave). The outcome is useful for public health transparency and epidemiology research by ensuring exposure data is accurate.

Introduction

Radiofrequency electromagnetic fields (RF-EMF) are electric and magnetic fields that travel together as waves. They are “non-ionizing”, meaning that they don’t have enough energy to break chemical bonds in atoms. The frequency range of RF-EMF is 3 kHz up until 300 GHz. This thesis focuses on the 5G New Radio (NR) n78 frequency band within the context of Belgium. Possible sources of RF-EMF exposure include base stations (using 3G, 4G LTE and 5G NR technologies), Wi-Fi routers, radio and television broadcasts, Bluetooth devices, microwave ovens and MRI machines. There are several reasons why RF-EMF needs to be monitored. First of all high RF-EMF exposure is linked with a range of biological effects, such as a possible increased risk of cancer (RF waves are classified as possibly carcinogenic by the WHO/IARC), thermal effects due to tissue heating, headaches and sleep disturbances [1]. Secondly, assessment changes in RF-EMF exposure within deployment areas (resulting from the continuous expansion of 5G NR base stations, Wi-Fi routers, and smart devices) can contribute to a more comprehensive understanding of the overall exposure landscape. Thirdly, continuous monitoring can help address public health concerns by publishing and interpreting exposure measurements, comparing them against established compliance guidelines, and thereby promoting transparency and fostering public trust in the deployment of emerging technologies. Lastly reliable exposure data is essential for epidemiological studies investigating long-term health impacts so evidence-based updates to exposure guidelines can be produced.

In the past several studies have been conducted to measure the time-averaged electric field strength E_{avg} and the maximum electric-field E_{max} of 5G NR MIMO (Multiple Input, Multiple Output) base stations such as the *in situ* measurement in Bern Switzerland [2] or in Düsseldorf Germany [3]. In order to enhance the efficiency of these exposure assessment campaigns a quadcopter could be used. An autonomous quadcopter with a 5G isotropic sensor will be developed and deployed to measure the E_{avg} , and E_{max} in the vicinity of the base station. The use of a drone significantly reduces the need for manual labour by researchers, enabling a more streamlined, flexible, and consistent data collection process in the three-dimensional space.

RF-EMF exposure guidelines are written by the International Commission on Non-Ionizing Radiation (ICNIRP) [4] in cooperation with research instances such as the Institute of Electrical and Electronics Engineers (IEEE). This independent commission of international scientists define the exposure limits of electromagnetic fields. ICNIRP was founded in 1992 by the International Radiation Protection Association (IRPA). Its mission is to evaluate and synthesize existing scientific knowledge and recent research findings in order to provide evidence-based guidance on protection against non-ionizing radiation, including radio waves (3 kHz – 300 MHz), microwaves (300 MHz – 300 GHz), infrared (IR) radiation (300 GHz – 430 THz) and ultraviolet (UV) radiation (750 THz – 3 PHz). The exposure guidelines are then recommended for implementation by the European Union to all member states, which coordinates harmonized adoption through formal recommendations and worker safety directives. More than 30 European countries have decided to incorporate the guidelines into national legislation or standards helping shape regulatory frameworks to protect the public and workers for harmful effects of non-ionizing radiation exposure [4-5].

1. Literature study

1.1 Radio frequency distribution in Belgium

By virtue of the Act of 13 June 2005 on electronic communications, the Belgian Institute for Postal Services and Telecommunications (BIPT) is in charge of managing the RF spectrum in Belgium, examining requests for its use and coordinating it on national and international level. The three Communities (Flemish, French, and German-speaking) are responsible for reviewing requests for the use of radio frequency spectrum intended for radio and television broadcasting [5]. The frequency spectrum bands of 3G, 4G-LTE and 5G NR in Belgium are shown in [Table 1-1](#). These spectrum bands are divided between the four main telecommunication providers in Belgium [6]. The portion of a frequency band allocated for uplink and downlink communication depends on the transmission technique used by the provider. In Belgium, Frequency Division Duplex (FDD), Time Division Duplex (TDD), and Supplementary Downlink (SDL) are employed. FDD is a communication technique in which both the uplink (transmission from the device to the network) and the downlink (transmission from the network to the device) occur on different frequencies. This approach allows for communication to occur in both directions at the same time, preventing signal interference and ensuring a reliable connection. In contrast, TDD operates by utilizing the same frequency for both uplink and downlink transmissions, but these occur in distinct time intervals. This method optimizes the use of available spectrum, particularly in scenarios where data traffic is uneven, such as when downloads outnumber uploads, as it permits the dynamic allocation of time slots based on current needs. SDL is a new technology used in LTE and 5G NR networks, which is employed to designate additional frequencies specifically for the downlink. This boosts download capacity, particularly in settings with high data demands, such as urban areas with high population densities, event venues like stadiums and crowded shopping malls. Both user devices and network equipment must support SDL for it to be used effectively, which limits the deployment of SDL [7-8]. The n78 band deploys the 5G NR technology, as focuses upon in [Section 1.2](#).

Table 1-1: Frequency bands of 3G, 4G-LTE and 5G NR in Belgium [7]

Frequency band name	Frequency division	
n28	FDD uplink (703 – 748 MHz)	FDD downlink (758 – 803 MHz)
n20	FDD uplink (832 – 862 MHz)	FDD downlink (791 – 821 MHz)
n8	FDD uplink (880 - 915 MHz)	FDD downlink (925 - 960 MHz)
n75	SDL (1432 – 1517 MHz)	
n3	FDD uplink (1710 - 1785 MHz)	FDD downlink (1805 – 1880 MHz)
n33	TDD (1900 – 1920 MHz)	
n1	FDD uplink (1920 - 1980 MHz)	FDD downlink (2110 - 2170 MHz)
n7	FDD uplink (2500 - 2570 MHz)	FDD downlink (2620 - 2690 MHz)
n78	TDD (3400 -3800 MHz)	

1.2 5G NR technology

1.2.1 5G Architecture overview

The 5G system architecture, as standardized by the 3rd Generation Partnership Project (3GPP), is designed to meet the diverse requirements of enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC). It comprises three primary components: User Equipment (UE), the Next-Generation Radio Access Network (NG-RAN), and the 5G Core Network (5GC) [9].

1.2.1.1 User Equipment

UE refers to devices such as smartphones, tablets, and IoT devices that connect to the 5G network. These devices are equipped with the necessary hardware and software to communicate over the 5G air interface, known as NR. It is the global standard for the 5G radio access technology, designed to support a wide range of frequencies (including sub-6 GHz and millimeter wave bands), higher data rates, and significantly reduced latency compared to previous generations [10]. To enable this, UEs incorporate advanced components such as multi-band antennas, high-performance baseband processors, and RF front-end modules capable of handling the dynamic beamforming and massive MIMO techniques used in 5G [11]. On the software side, 5G UEs implement NR protocols that manage functions like channel coding, scheduling, and mobility, allowing seamless communication with the 5G base stations (gNodeBs) [12]. These capabilities make NR-based UEs essential for delivering the high-speed, low-latency experience expected from 5G networks [13].

1.2.1.2 Next-Generation Radio Access Network

The NG-RAN provides the wireless communication link between the UE and the 5GC. Its main element is a gNodeB (gNB), which manages radio transmissions and supports advanced technologies such as Massive MIMO and beamforming. The gNB is the 5G base station, connecting user devices to the 5GC using the NG interface. It handles both user and control plane protocols and carries out much of the work required for efficient data transmission and mobility management [10]. To achieve higher data rates and improved coverage, gNBs use Massive MIMO technology, where a vast number of antennas are employed to serve multiple users with the same resource. This concept is what drastically increases spectral efficiency and network capacity. Moreover, beamforming is used to focus beams of radio signals directly to user equipment, hence reducing interference and improving the strength of the signals [14].

1.2.1.3 5G Core Network

5GC is an important evolution of past mobile core networks, with a cloud-native and service-based architecture that offers greater flexibility, scalability, and efficiency [10]. The 5GC is made up of different specialized network functions, with each performing an important part of managing user connections and data transmission within the network. A key first component that a UE communicates with once it joins the 5G network is the Access and Mobility Management Function (AMF). The AMF performs signaling procedures including user registration, authentication, connection establishment, and mobility management [15]. It is the portal to the 5GC and maintains signaling connections and provides continuity of service as the UE moves between different base stations (gNodeBs). When UE is authenticated and registered, session management will be performed by the Session Management Function (SMF), which will set up, update, and release PDU (Packet Data Unit) sessions. It assigns IP addresses to UE, enforces data treatment policies, and chooses the User Plane Function (UPF) to handle actual data transmission [15-16].

User Plane Function (UPF) processes user plane data and carries out basic operations including packet forwarding and routing, traffic shaping, usage reporting, and Quality of Service (QoS) rule enforcement as defined by the SMF. It is also responsible for acting as a link between data networks outside and the RAN (through the gNB) to deliver user data to its desired location efficiently. These functions communicate with one another through Service-Based Interfaces (SBIs), which enable functions to register, find, and engage dynamically through HTTP/2 and RESTful APIs. It supports modularity, flexibility, and simplified deployment of services and network slices [10]. During a normal UE connection process, the UE initially sets up signaling connection with the AMF, which verifies and handles mobility for the user. The AMF, in turn, communicates with the SMF to establish a session, and the SMF selects a UPF to forward user traffic. Such a pipeline allows both user data and signaling to be directed through paths that are optimized for the user's requirements and network conditions [15-16].

1.2.1.3 Network slicing, Multi-Access Edge Computing, Service-Based Architecture

A unique characteristic of 5G architecture is network slicing, which supports creating numerous virtual networks over shared physical infrastructure. Each slice is designed for particular service needs, e.g., URLLC or eMBB, to optimize the utilization and delivery of resources and service. The method supports operators to deliver differentiated network experiences to various applications, ranging from autonomous vehicles to large deployments of IoT applications [17].

Multiple-Access Edge Computing (MEC) brings computing functionality to the edge of a network, nearer to end-users. Processing data locally, as opposed to at centralized cloud servers, minimizes latency and accommodates latency-sensitive applications such as autonomous driving and augmented reality. It improves user experience and allows for innovations which demand instant data processing [18].

Service-Based Architecture (SBA) in 5G supports deploying network functions as separate, individually created and scaled modular services. The design improves the adaptability and agility of the network to enable quick launch of new features and services. Operators, through SBA, can effectively control network resources and react to dynamic service requirements quickly [10].

1.2.2 Key Technologies in Physical Layer of 5G

1.2.2.1 Orthogonal Frequency Division Multiplexing

5G NR employs Orthogonal Frequency Division Multiplexing (OFDM) to allocate the available bandwidth into several narrowband subcarriers, spaced orthogonally to prevent interference and increase spectral efficiency, as seen in [Figure 1-1](#). It allows for high data rates, even for dispersive channels. A cyclic prefix (CP) is appended to every OFDM symbol to counteract intersymbol interference and maintain subcarrier orthogonality. OFDM is appreciated for its immunity to channel dispersion and simplicity of channel estimation, but at the cost of high peak-to-average power ratio (PAPR) and sensitivity to frequency and phase noise [19]

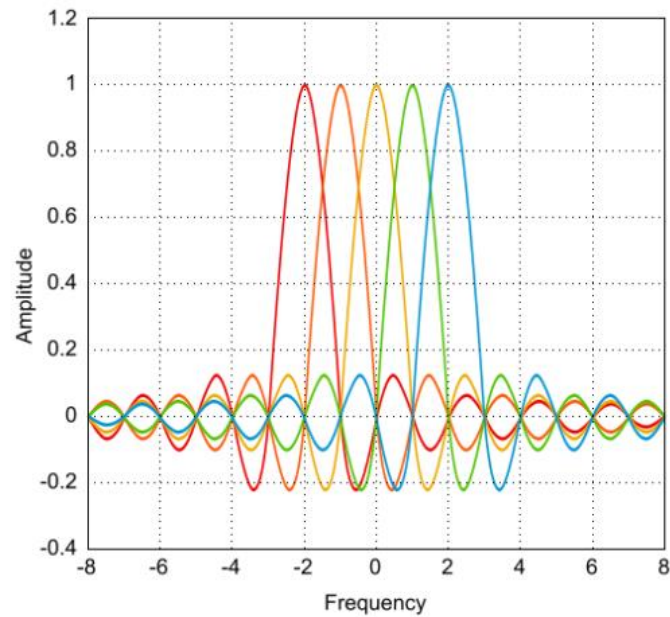


Figure 1-1: OFDM (Orthogonal Frequency Division Modulation) [21]

1.2.2.2 Massive MIMO

Massive Multiple-Input-Multiple-Output (MIMO) extends conventional MIMO systems by having tens to hundreds of base-station antennas, as in [Figure 1-2](#). Large-scale arrays of antennas provide the ability to serve many users at once, and in turn, a single-antenna device per user, using spatial multiplexing. The illustration shows how every base-station antenna communicates on a Massive MIMO channel to many users, creating distinct signal pathways per user. This method greatly improves spectral efficiency and link reliability.

One of the benefits of Massive MIMO, as shown, is channel hardening—the sheer quantity of available propagation pathways smooths out abrupt channel fades, allowing more stable and predictable connections. This lends itself naturally to high-density city use and facilitates the scaling necessary in 5G networks [20].

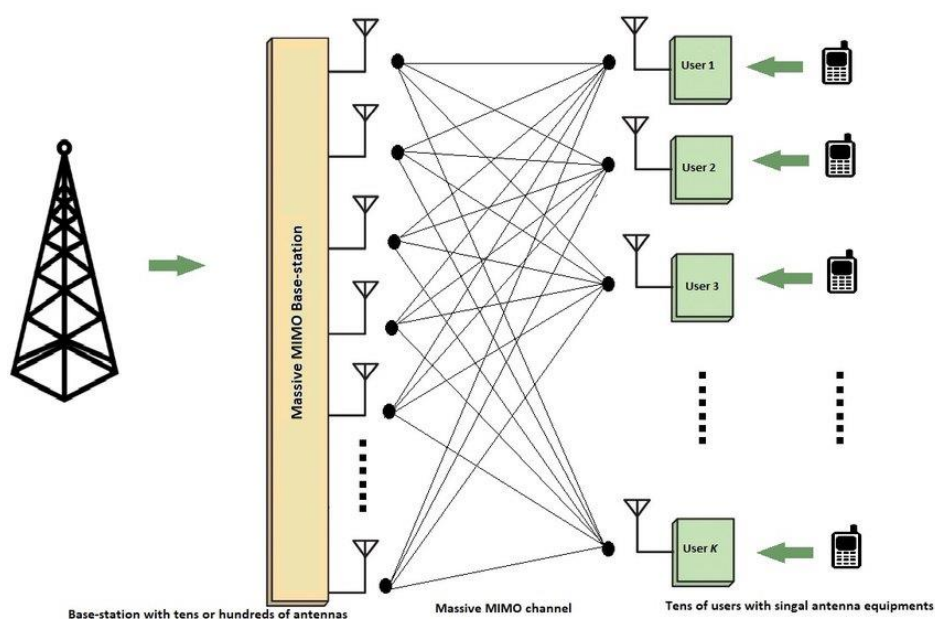


Figure 1-2: MIMO base station, MIMO channel and K UE devices [21]

1.2.2.2 Beamforming

In the 5G system, beamforming is implemented to guide the base stations energy in a particular user or spatial direction by control of the amplitude and the phase of the transmitted signal from many different physical antennas placed on a base station. Instead of transmitting the same exact signal, every physical antenna (or subarray of antennas) sends a replica of the signal different in phase ϑ and, optionally, amplitude A modified as well. Such synchronized transmission generates constructive interference in the direction of interest and destructive interference in other areas, effectively building a focused beam.

Assume a transmitted signal $S(t)$, as illustrated in [Figure 1-3](#). On the left there is a single antenna element radiating that signal, the beam is omnidirectional in nature, spreading equally in multiple directions. There is no amplitude or phase control, which results in no directivity nor gain. In the second image, a 1D linear antenna array is shown transmitting the same signal $S(t)$ but now amplitude A_i and phase ϑ_i control are introduced. When the signal is radiated through neighbouring antenna elements in a progressive phase displacement, like $S_i(t) = A_i \cdot S(t + \vartheta_i)$, the wavefronts of the signal from every antenna element overlap at different in the vertical plane. The right image highlights a 2D planar array is introduced which allows beamforming in both azimuth and elevation planes. Each antenna element sends the base station signal $S(t)$ with and independently weighted amplitude A_{ij} , vertical phase shift ϑ_i , and horizontal phase shift ϕ_j . The output signal becomes $S_{ij}(t) = A_{ij} \cdot S(t + \vartheta_i + \phi_j)$. This technique enables 3D beam steering, crucial for precisely targeting UE's from users. [22]

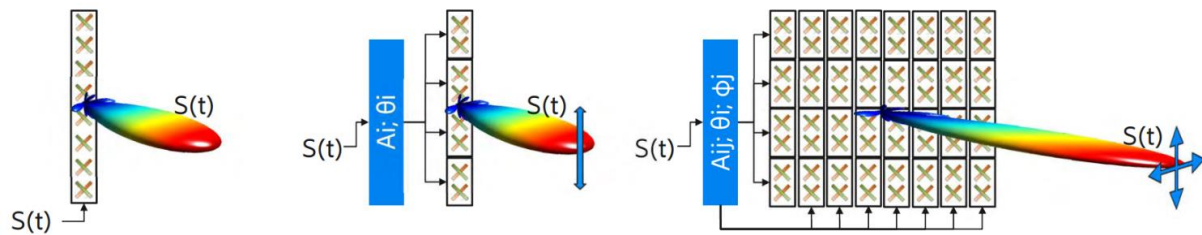


Figure 1-3: Three antennas with subarrays that that can change 2D (second antenna) and 3D directions (third antenna) by adjusting amplitude and phase change [25]

The direction of the beam (angle of maximum radiation) is determined by the phase gradient across the antenna array in both the horizontal (azimuth) and vertical (elevation) dimensions. Meanwhile the beam shape is determined by the spacing between and the number of subarrays. As the number of subarrays grows, the beam's primary lobe becomes narrower and more focused, leading to higher beamforming gain. This strengthens the signal at the target receiver while minimizing interference to and from other directions. In a 2D planar array (used for 3D beamforming), each antenna element located at position (i, j) is assigned a specific phase shift $\Delta\phi_{ij}$ to steer the beam toward a desired direction defined by azimuth angle ϕ and elevation angle. [Equation 1.1](#) defines the phase shift:

$$\Delta\phi_{ij} = \frac{2\pi}{\lambda}(i \cdot d_x \cdot \sin(\theta) \cdot \cos(\phi) + j \cdot d_y \cdot \sin(\theta) \cdot \sin(\phi)) \quad (1.1)$$

Where:

- λ is the wavelength
- d_x, d_y are the spacings between antenna elements along the x (horizontal) and y (vertical) axes
- ϕ is the azimuth angle
- θ is the elevation angle
- i and j are the indices of the antenna element in the 2D array

Beamforming is commonly used in Multiple input Multiple Output (MIMO) applications. Rather than transmitting a single high-power signal in all directions multiple narrow low-power beams will transmit the data towards the UE. This is done to achieve lower overall transmit power, which increases battery life, reduces heat and lowers interference at the base station. A highly concentrated signal will also improve the Signal-to-Noise Ratio (SNR). A higher SNR means that the signal is much stronger than the background noise, making it easier for the receiver to distinguish the signal accurately. This allows the use of higher-order modulation schemes, which carry more bits per symbol, thus increasing data rates. It also reduces errors and retransmissions, improving connection reliability.

There are two different types of traffic beams. Reciprocity-based beamforming and Codebook based beamforming, each with its own characteristics. In Reciprocity-based beamforming, the UE transmits the Sounding Reference Signals (SRS), which the base station uses to determine the beam direction, shape, and number of beams tailored to the current channel conditions, this process is illustrated in [Figure 1-4](#). In TDD systems the uplink and downlink communication uses the same frequency just at different times. Because of this the physical characteristic of the wireless channel (like reflection, diffraction and fading) remain mostly constant in this bidirectional communication, at least over short time intervals. This principle is known as channel reciprocity. This approach allows for fine-grained, real-time beam adaptation, making it highly effective in environments with rapidly changing channel characteristics or user mobility. Moreover, it reduces feedback overhead from the UE, since the base station handles most of the beam management independently. This efficiency makes reciprocity-based beamforming especially well-suited for massive MIMO deployments in dense urban areas [23].

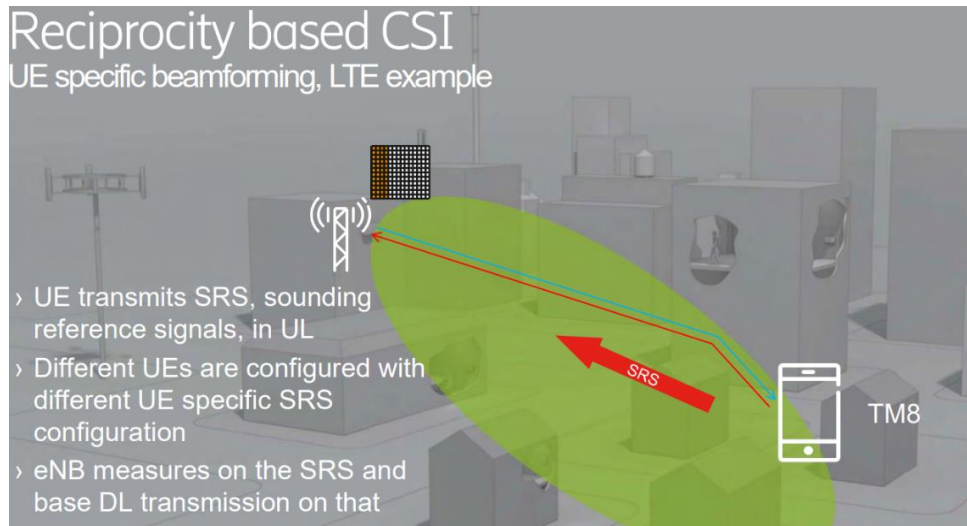


Figure 1-4: Reciprocity base CSI [25]

In closed-loop CSI feedback, the beamforming process is regulated by feedback based on the reference signals transmitted by the base station. The base station transmits CSI-Reference Signals (CSI-RS) to the UE on a periodic basis. The UE utilizes the CSI-RS to assess parameters to evaluate the channel like path loss, fading, and some selected aspects of spatial purity [24]. Using the CSI-RS, upon reception, the UE performs a channel estimation and selects a precoding matrix (or beam) from the three-dimensional predetermined designating (3GPP code book) reporting inferences the optimum transmission for the prevailing provided environment. The UE sends the CSI report to the base station along with the parameters of ACM, which includes: Precoding Matrix Indicator (PMI), Rank Indicator (RI), and Channel Quality Indicator (CQI) [25]. Then, using the feedback from the UE, the base station is able to create an appropriate max SNR beam that takes into consideration the location of the UE, and the channel conditions, the total process is describe in [Figure 1-5](#). The closed loop channel estimation provides a way for dynamic adaptive beamforming which minimizes interference and hence improves the system performance in terms of efficient use of the spectrum. Furthermore, optimizing of the SNR, and data throughput ultimately increases the link reliability and is designed to counter issues stemming from frequency selective propagation channels, and/or time varying environments where the channel changes instantaneously, while there is no significant interaction in delays experienced by the intended target users [23-26].

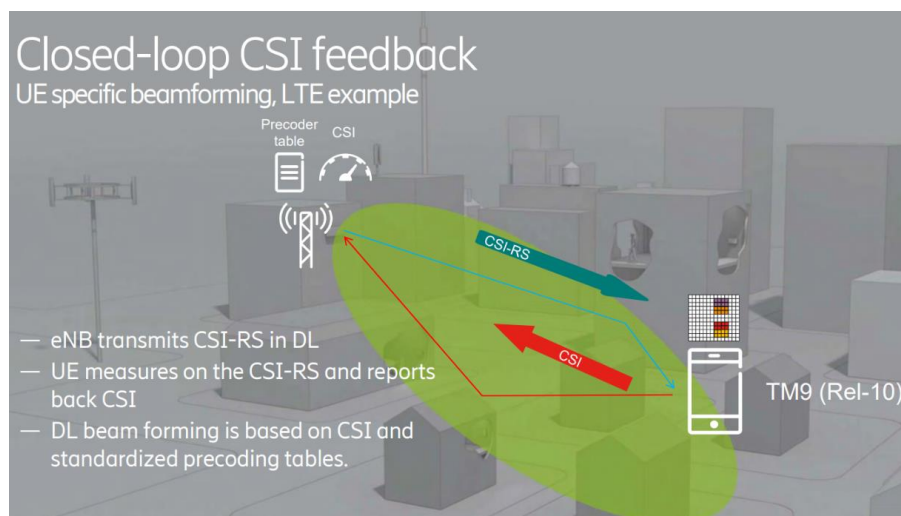


Figure 1-5: Closed-loop CSI feedback [25]

1.2.2.3 Frequency Bands Utilization

The 5G networks operates across a different spectrum of frequency bands. Each frequency band is typically linked with certain deployment scenarios. The deployment scenarios vary on different metrics such as coverage, penetration depth and capacity. Coverage refers to the ability of a network to reach a wide area and provide connectivity in it. It measures how far a signal can travel from the base station, while still providing a reliable connection. Penetration depth highlights the capability of how well a network signal is able to pass through physical barriers such as walls, buildings or other obstacles. The capacity refers to how much data can be transmitted through the network at any given time. This mainly depends on the frequency spectrum, higher frequencies can carry more data due to their larger available bandwidth.

The first one is Low-Band (<1GHz). Low-Band provides extensive coverage and deep penetration. It can cover larger rural or suburban areas with fewer base stations. This is because the signals can propagate over long distances and can easily pass through obstacles like scarce buildings or trees. The longer wavelength of Low-Band makes it easier to penetrate obstacles. The second one is Mid-band (1-6 GHz). Almost all base stations that are currently deployed operate in this Mid-Band frequency range. It offers a balance between coverage and capacity, so it can handle more data than low-band while still offering decent coverage, making it suitable for urban and suburban areas. High-Band (mmWave > 24 GHz) contain the highest capacity. These high frequencies support much larger bandwidths. This creates really low-latency perfect for urban areas and high-demand applications. Ultra-Reliable Low Latency Communications (URLLC) is a feature that is active in the high-band (mmWave) spectrum, it aims to deliver end-to-end latency as low as 1 millisecond, coupled with extremely high reliability.

1.2.2.4 Initial Access and Synchronization

The initial access in 5G NR is a crucial step in which a User Equipment (UE) identifies, synchronizes, and gets connected to a cell. This is started by the detection of the Synchronization Signal Block (SSB), including the Primary Synchronization Signal (PSS), the Secondary Synchronization Signal (SSS), and the Physical Broadcast Channel (PBCH). These together deliver the necessary information to facilitate time-frequency synchronization and cell identity acquisition [27]. The SS/PBCH block is transmitted in a periodic manner and is also tasked with the synchronization of UE in both time and frequency domains. It lasts four OFDM symbols in time and 240 subcarriers (amounting to 20 MHz in the 15 kHz Sub Carrier Spacing (SCS) case) in frequency, which is equivalent to 12 resource blocks (RBs). It provides constant power of transmission and hence is detection robust even under harsh radio conditions .

Previously, LTE had a static centre frequency for synchronization signals. 5G NR, however, provides frequency flexibility through the Global Synchronization Channel Number(GSCN). The centre frequency of the SS/PBCH block (commonly referred to as the f_{SSB}) is no longer static and can be dynamically configured depending on the defined raster, allowing flexibility in deploying the 5G in a broad spectrum of frequency ranges — ranging from sub-1 GHz to mmWave [28].

[Figure 1-6](#) presents the time-frequency structure of the SS/PBCH block and how the PSS, the SSS, and the PBCH are allocated in subcarrier index and OFDM symbol positions. PSS is responsible for symbol timing synchronization and sector identification, whereas the SSS conveys the frame time and parity data for the calculation of the cell ID. Subsequently, the PBCH conveys the Master Information Block (MIB), which contains system bandwidth and SSB periodicity cell configuration [29].

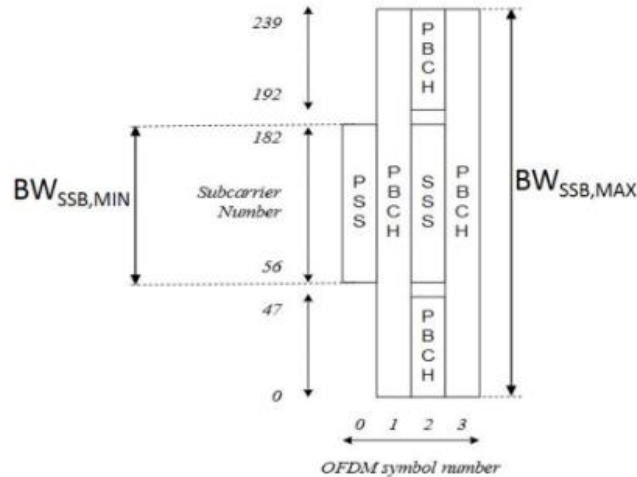


Figure 1-6: Time and frequency structure of the SS/PBCH block [3]

1.2.2.5 Sub Carrier Spacing in 5G

In contrast to 4G Long Term Evolution (LTE), where the SCS had a fixed value of 15 kHz, the scalable numerology is a new feature of 5G NR in which SCS can vary with μ :

$$SCS = 2^{\mu} * 15kHz \quad (1.2)$$

Where:

- SCS is the Sub Carrier Spacing [kHz]
- μ is a parameter ranging from [0,4]

Values for μ ranging from 0 until 4 correspond with a SCS of 15, 30, 60, 120, and 240 kHz respectively [30]. This flexible subcarrier spacing facilitates NR to efficiently support different frequency ranges and use cases:

- Lower μ (15 or 30 kHz) is preferred for coverage and mobility in Sub-6 GHz bands (Low-Band and Mid-Band).
- Greater μ (for instance, 120 or 240 kHz) is reserved for frequencies in the mmWave, supporting low latency and high bandwidth transmission.

The time-frequency grid in 5G NR is organized in Resource Blocks (RBs). One RB comprises 12 consecutive subcarriers in the frequency dimension and one time slot, in which the time duration of one time slot varies based on the applied SCS. For instance, when using 15 kHz SCS, one time slot is 1 ms, while using 30 kHz it is 0.5 ms, and so on. Depending on the carrier bandwidth and subcarrier spacing, the number of RBs (NRB) supported varies, the maximum being up to 100 MHz in Sub-6 GHz levels and up to 400 MHz in case of mmWave frequencies [3]. This dynamic architecture provides flexibility to accommodate a variety of services, from high-throughput eMBB to low-latency high-reliability URLLC through the adaptable time-frequency structure in line with the characteristics of the spectrum and the requirements of the performance.

1.2.3 Key Technologies in Network Layer and Application Layer of 5G

In the network layer, Software Defined Networking (SDN) and Network Function Virtualization (NFV) are critical enablers of a programmable and flexible 5G core.

SDN separates the control and data plane. The control plane is responsible for making decisions about where network traffic should be set (routing, policies, etc.). The data plane is responsible for forwarding

traffic to the selected destination. Imagine a 5G network where users are streaming HD video, browsing the web, and using IoT devices simultaneously. Using a SDN software-based controller the operator will detect video traffic and automatically allocate more bandwidth to those data flows, route latency-sensitive Internet of Things (IoT) messages over the lowest-latency path and reroute traffic instantly if a link fails. This level of flexibility enables efficient resource use, faster service deployment, and better quality of service (QoS) for different 5G applications [31].

Network Function Virtualization (NFV) is one of the primary concepts in present-day networking and refers to the execution of network functions like load balancers, firewalls, gateways, and intrusion detection systems as software instances on generic servers, not dependent on specific proprietary hardware. NFV employs virtual machines (VMs) or containers, under the control of a hypervisor or orchestration layer, to deploy these capabilities flexibly in the cloud environment. This permits telecom operators to scale the services on demand, change in response to shifting traffic, and save considerably on capital and operating costs. Whereas SDN manages the control and programmability of the network in a centralised manner, NFV provides a virtualised ability to virtualize the real functions that process and regulate the network traffic—thus, they are strongly complementary technologies [32], this cooperation is illustrated in [Figure 1-7](#). SDN and SDN and NFV are the foundation of the architecture of the network slicing in 5G; the network slicing is a foundational architecture innovation that makes it possible for the operators to create confined, end-to-end virtual networks, tailored to a given use case. They can optimize the slices in line with the selected service in terms of its respective performance metric, i.e., latency, reliability, or bandwidth [33].

In the context of the 5G NR systems, beamforming is utilized to send the Synchronization Signal Block (SSB) in several pre-defined spatial directions, referred to as beams, in the so-called SS burst set. The beamforming transmission in several directions guarantees the base station can effectively reach UEs in different spatial areas, in the presence of high path loss, like the mmWave bands. Multiple beams raise the likelihood of the new radios initial access by enhancing the detectability of the signal and the coverage, and diminishing interference that occurs in every direction [29].

An SS burst set contains one or more SS bursts, one of which contains a series of SSBs broadcast in different beam directions. These burst sets are sent in a periodic manner, and the possible periodicities include values of 5, 10, 20, 40, 80, or 160 milliseconds, of which the default is 20 ms. One SS burst is transmitted in a time window of 5 ms in which the set of beamformed SSBs are transmitted sequentially [24]. Such a systematic and periodic scheduling provides UEs with a reliable opportunity to detect and sync up with the network, even in poor network conditions.

How NFV and SDN work together

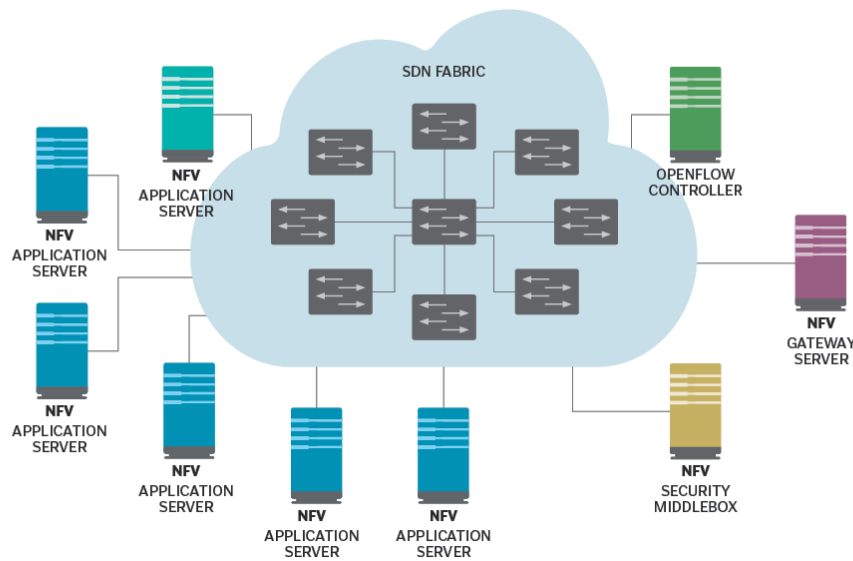


Figure 1-7: NFV and SDN cooperation [34]

At the application layer, 5G facilitates three major, service categories, which the 3rd Generation Partnership Project (3GPP) defines: Enhanced Mobile Broadband (eMBB), - this category can support everything ranging from high data rate video streams of the ultra HD type (4K, 8K+) up to AR and VR-based services, which demand high data rates. Ultra-Reliable Low-Latency Communication (URLLC)- the service is optimized especially for mission critical use, i.e., autonomous car communication or remote industrial automation. Massive Machine-Type Communications (mMTC)- the service type supports a broad set of health and wealth monitoring in the absence of the battery and computing resources against the degradation of performance [35]. Some more applications based on these service categories are showcased in [Figure 1-8](#).

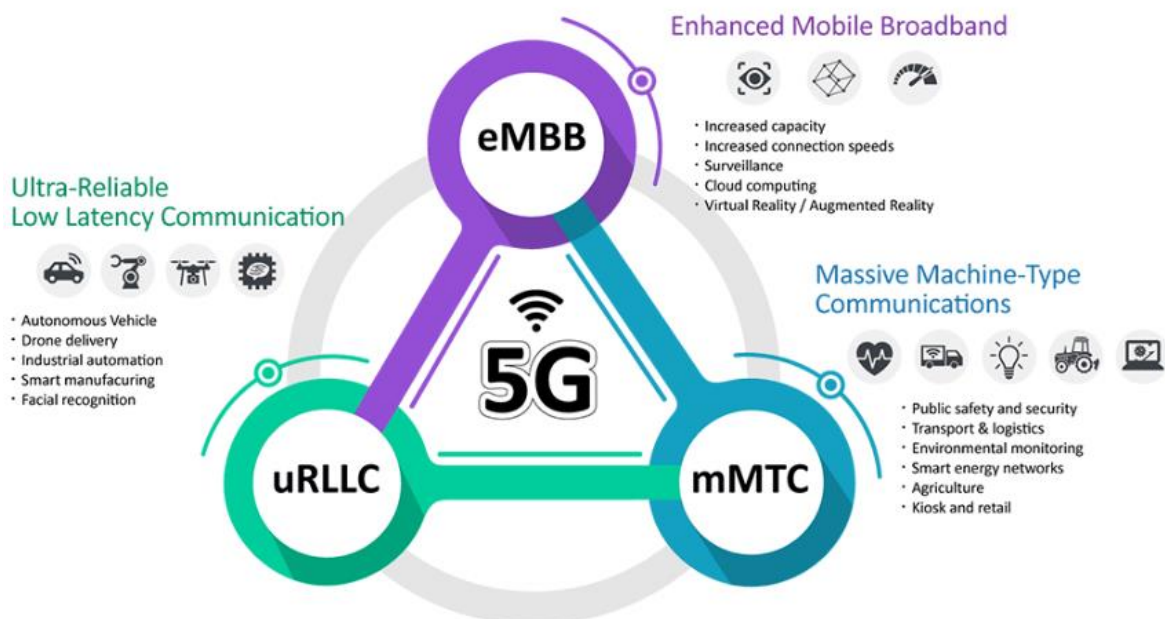


Figure 1-8: eMBB, uRLLC and mMTC applications

1.3 RF-EMF

1.3.1 Biological effects on humans

Several studies have reported associations between high levels of RF-EMF exposure and non-specific symptoms such as headaches and sleep disturbances. However, definitive scientific evidence demonstrating a direct causal link between RF-EMF exposure and the reported symptoms remains absent. There is a minority of the population that suffers from a condition called Idiopathic Environmental Intolerance to EMF (IEI-EMF), also known as “hypersensitivity to EMF” [36]. The symptoms vary between individuals, with severe headaches and sleep disturbances being the two most common symptoms [38-40]. To date, cluster analyses have failed to identify distinct symptom groups directly associated with specific EMF exposure sources or EMF exposure in general and the symptom patterns do not appear to correspond to any recognized syndrome [37].

The interaction between the human body to RF-EMF signals is influenced by two major factors: exposure intensity and frequency. When frequency is increased, the depth to which electromagnetic waves can penetrate biological tissues typically decreases, with higher-frequency waves being absorbed more superficially. The exposure intensity refers to the magnitude of the electric and magnetic fields, or the power density to which a body is exposed, and can vary based upon whether exposure is acute or chronic. Apart from these main factors, there are various other factors that contribute to how RF-EMF interacts with biological processes. There is exposure duration, signal modulation, polarization, and dielectric properties of involved tissues. Each of these variables, in conjunction with one another, accounts for distribution and absorption of energy in the body, which in turn affects likely biological outcomes in various exposure situations. In most simulations, the Specific Absorption Rate (SAR, measured in W/kg of tissue) is the primary metric used to assess exposure, however this cannot be measured in the field. SAR, when multiplied by exposure time, reflects the total RF-EMF energy dose absorbed by the body or specific tissues. In all experimental studies in the field only other EMF exposure metrics, such as electric field strength or power density can be directly measured. This is resolved because the basic SAR restrictions were translated into so-called reference levels (root-mean-square (RMS) values) for the electric field strength E in (V/m), magnetic field strength H in (A/m) and for the power density S in (W/m^2) [4].

C. Baliastas et al. researched IEI-EMF and developed a list of criteria with various symptoms ranging from category A1 (minor adverse health effects attributed to EMF exposure) to category H (five symptoms or more experienced weekly for three consecutive months). In total sixty-three studies until June 2011 were included in the study, containing 35 experimental studies and 28 observational studies. The main criteria for a previous study to be included were: 1) Self-report of being (hyper)sensitive to EMF. 2) Attribution of non-specific physical symptoms (NSPS) to at least one EMF source. 3) Absence of medical or psychiatric/psychological disorder capable of accounting for these symptoms. 4) Symptoms should occur soon (up to 24 hours) after the individual perceives an exposure source or exposed area. (Hyper)sensitivity to EMF was either generalized (attribution to various EMF sources) or source-specific if the source was known. Experimental studies used a larger number set of criteria than those of observational design and performed more frequently a medical examination or interview as prerequisite for inclusion. After a study was included its data was further analysed with the criteria ranging from A1 to H, as earlier mentioned. [Figure 1-9](#) shows the prevalence in % of these criteria in the included studies. It can be concluded that a substantial portion of individuals report experiencing adverse health effects attributed to EMF (category A1), but the prevalence decreases significantly as the criteria become more stringent and involve more frequent and severe symptoms (towards category H). This indicates that the more broadly defined definitions of IEI-EMF include a larger percentage of people than the more restrictive and symptom-heavy definitions [36].

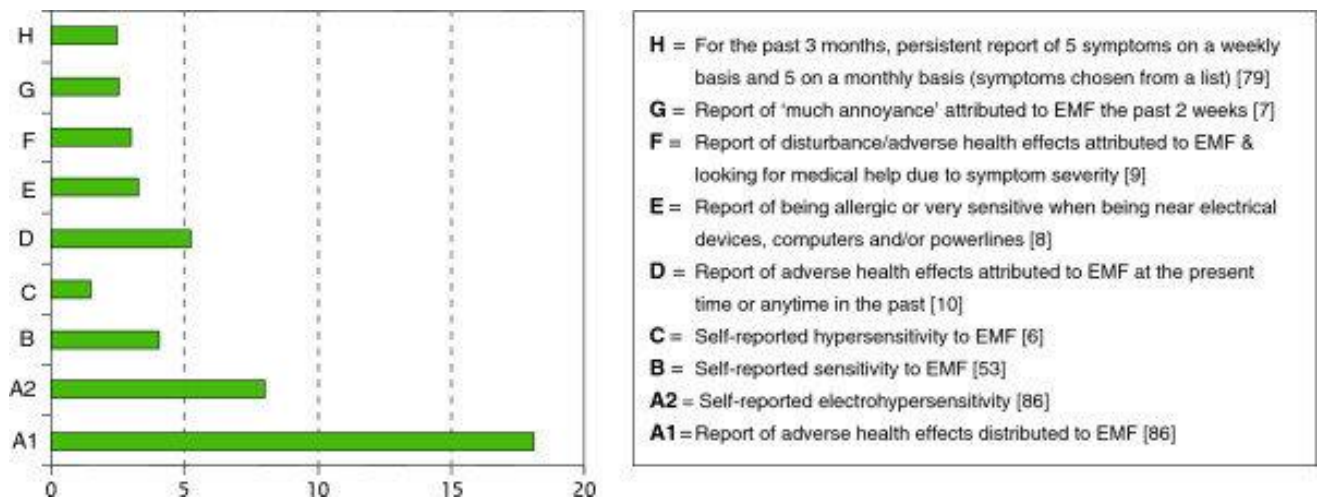


Figure 1-9: The prevalence in % of certain criteria (ranging from A1 to H) being met in the 63 included studies [36]

1.3.2 Scientific foundations and Regulatory Implementation of ICNIRP RF-EMF Exposure Limits
 ICNIRP defines science-based limits for non-ionizing radiation exposure, including 5G, to protect health. These guidelines are supported by the EU and widely adopted across Europe [4-5], as stated in the [introduction](#). For high-frequency electromagnetic fields (100 kHz-300 GHz, which include 5G NR) the main objective is to limit all temperature increases to 1°C for whole-body exposure and to 5°C for limbs and 2°C for the head (local exposure) [4].

A reduction factor of 50 for the general public and 10 for occupational settings is applied on the derivation of the external field limits (E, H and S) from the basic SAR restrictions to account for different levels of exposure and vulnerability between the general public and occupational settings. The general public is considered a more vulnerable and also uninformed population, containing children and individuals with health issues. Therefore a larger safety margin is applied. In occupational settings workers are assumed to be adults, who are aware of the risks and can control their exposure to a greater extent by wearing protective gear, such as shielding clothing. The whole-body average reference levels for the public are based on the power density for frequencies higher than 2 GHz [4]. [Figure 1-10](#) shows that the 2019 ICNIRP guidelines allow a power density of 10 W/m². This results in a maximum electric field of 61,7 V/m.

$$E = \sqrt{S \cdot Z_0} = \sqrt{10 \frac{W}{m^2} \cdot 377 \Omega} = 61,7 \frac{V}{m} \quad (1.3)$$

Where:

- S is power density in [W/m²]
- Z_0 is the resistive impedance of free space [Ω]

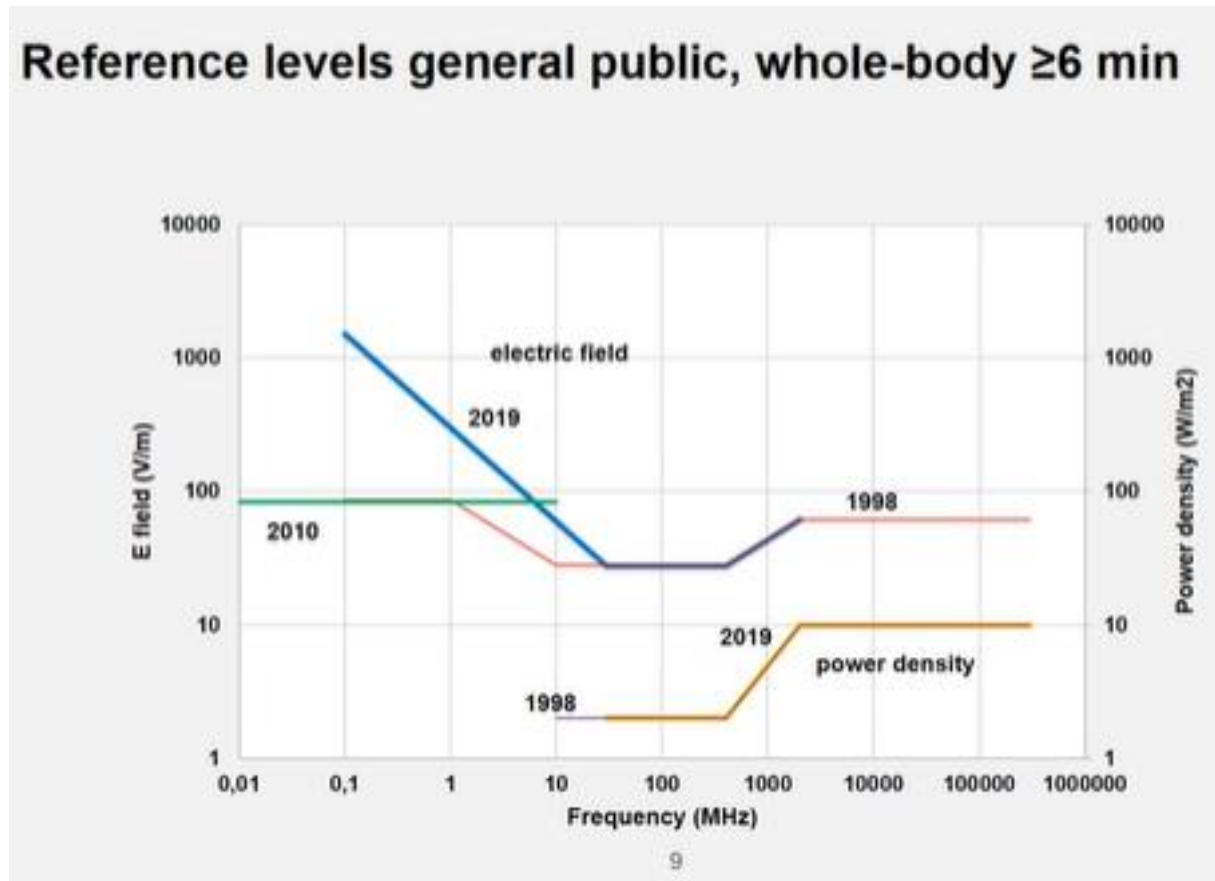


Figure 1-10: Reference levels of the general public, whole body (more than 6 min) [38]

1.3.3 Near-field and far-field regions

Compliance assessments compare RF-EMF field measurements to ICNIRP reference levels, often requiring distance measurements from the radiation source. However, this is challenging in non-line-of-sight (NLOS) scenarios, especially since near-field data is typically not captured in standard assessments but measurements are taken in the far-field region. The distance until the RF-EMF source is divided into two categories. The far-field region is evaluated with the standard IEC 62232, using the measurement procedure listed in the ICNIRP guidelines [39]. In the near-field both electric and magnetic field levels must be measured [40]. The transition between the near-field and far-field regions is not fixed but depends on the operation frequency and physical dimensions of the antenna. The Fraunhofer distance is a commonly accepted boundary for the beginning of the far-field regions [41].

$$R = \frac{2D^2}{\lambda} \quad (1.4)$$

Where:

- R is distance for the physical antenna [m]
- D is the maximum dimension of the antenna aperture [m]
- λ is wavelength [nm]

For base station antennas operating in typical mobile communication bands (700 MHz to 3.9 GHz), the far-field region is generally assumed to begin at distances between 5 and 20 meters from the base station. Determining whether the test point is in the near-field or far-field is essential to choose the right probe and measurement method. The electric field strength is not enough in the near-field since

there are reactive fields present along with no fixed ratio of E/H . It is necessary to use both the E-field probe and H-field probe in the near-field. In the far-field, electric field strength alone is adequate since there is radiation Z_0 present in the field with an impedance of about 377Ω [42].

1.3.4 RF-EMF sensors

1.3.4.1 SDR-based RF-EMF measurement techniques

A Software-Defined-Radio (SDR) is a software-programmable RF communication system that is capable of both transmitting and receiving. The architecture enables the implementation of conventional RF front-end devices, such as filters, amplifiers, modulators, demodulators, synchronizers, and detectors in software. They are normally implemented near the antenna with the help of software frameworks for digital signal processing. The software-based solution offers programmability and accommodates in-time updating through frameworks such as GNU Radio, MATLAB, or Python. Various studies have considered SDR usage in measurement of RF-EMF exposure, such as implementations of broadband field meters, dual-band measuring nodes, and FFT-based spectrum analyzers. They are low-cost in comparison to other sensors such as commercial exposimeters or area monitors [43].

1.3.4.2 Hardware sensors

This thesis employs a triaxial hardware sensor, which is receptive to 5G NR to measure the RF-EMF exposure in the n78 band in Belgium. The difference between hardware sensors and SDR's is that the filters, RMS detectors, amplifiers and modulators are specifically configured for measuring a specific frequency and this frequency can't be configured via software. The only thing that is read through software is the analog-to-digital converter (ADC) RMS detector voltage value. In most hardware sensors an RF power detector is integrated to measure the received signal strength. These power detectors generate a DC output voltage, which linearly, exponentially or logarithmically corresponds to the RMS or LOG value of the measured power signal in [dBm]. It is then sampled by an analog-to-digital converter (ADC). The signal is then processed by a microcontroller or processor, converting it into a power level using a lookup table. During an onboard-calibration a signal generator incrementally increases the transmitted power, while the device records the resulting detector output voltage. The power level in [dBm] is then translated into the corresponding electric field strength [V/m] using the Antenna Factor (AF). The AF is a frequency-dependent conversion coefficient that relates the incident electric field strength to the voltage measured at the antenna terminals, and is defined as:

$$AF(f) = \frac{E(f)}{V(f)} \quad (1.5)$$

Where:

- $E(f)$ is Electric field strength in [V/m]
- $V(f)$ is Voltage measured at a power detectors antenna [V]
- $AF(f)$ is Antenna factor in [$1/m^2$]

The AF is determined through laboratory calibration in a controlled electromagnetic environment, such as an anechoic chamber, where the field strength and conditions are precisely known and consistent.

Power density S is calculated using equation 1.6. Then the power density is used to calculate the electric field strength E using the resistive impedance of free-space Z_0 using equation 1.7.

$$S = \frac{P}{AF} \quad (1.6)$$

$$E = \sqrt{S * Z_0} \quad (1.7)$$

Where:

- S is Power density [W/m^2]
- P is Power [W]
- AF is Antenna factor [$1/\text{m}^2$]
- Z_0 is the resistive impedance of free space [Ω]

[Figure 1-11](#) shows two examples of hardware sensors. Broadband measurement devices are intended to measure the RF-EMF exposure over a broad frequency range, including more than one RF band at a time. The instruments give a single, cumulative value, the overall electric field strength E or power density S , over the entire operational frequency range. Although broadband measurement devices are useful for rapid and overall measurements, they do not identify each signal source or frequency band. Frequency-selective measurement devices can identify and analyse individual frequency components of the RF spectrum. These devices can measure E or S for one or several narrow frequency bands, thus enabling the determination and measurement of a single transmitter or technology, including Wi-Fi, 4G LTE or 5G NR signals. In [Figure 1-11a](#) the WAVES sensor from Deprez et al. is showcased. This device measured the following four frequency bands: 1) 791-821 MHz; 2) 925-960 MHz; 3) 1805-1880 MHz and 4) 3550-3700MHz [44]. This is an example of a frequency-selective hardware sensor. [Figure 1-11b](#) highlights an Add-on sensor with a frequency range from 100 to 8000 MHz [45]. This is an example of a broadband SDR.

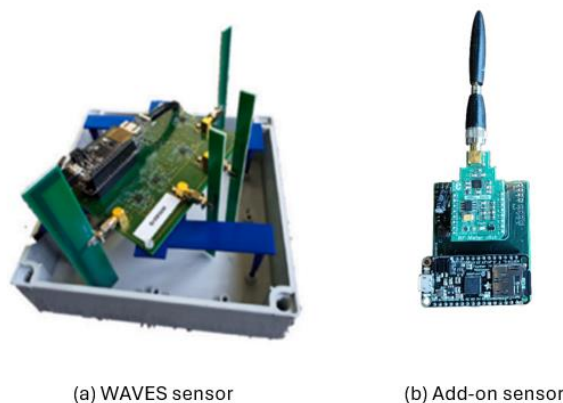


Figure 1-11: Hardware sensor WAVES sensor (a) Add-on broadband probe (b)

1.3.4.3 Field Strength Analyzer

[Figure 1-12](#) illustrates the Narda SRM-3006, a portable narrowband field strength analyzer designed for precise measurement of electromagnetic fields. It is a complete and easy-to-use isotropic measurement device. Due to its ease of use, high precision, and compliance with international measurement standards, it is widely recognized as the gold standard in RF-EMF exposure assessment and is frequently employed by governmental and regulatory bodies for compliance assessments. For

this study the tri-axial antenna (3502/01) with a frequency range of 420 MHz to 6GHz was used. This device is frequency-selective. The device offers both peak detection and spectral integration capabilities. By measuring the electric field strength E in a anechoic chamber with this device and measuring the received power P_r with a hardware sensor (and keeping the RF-EMF source exposure constant) the Antenna Factor AF can be calculated using equations 1.6 and 1.7 [44].



Figure 1-12: Field Strength Analyzer SRM3006 [46]

1.3.3 Measurement protocols

A quadcopter drone equipped with a frequency-selective triaxial 5G NR hardware sensor will measure RF-EMF exposure in the n78 band (3.4–3.8 GHz) in Belgium. The hardware sensor covers the 3.4–3.9 GHz range, ensuring accurate detection of all exposure in the n78 band. The sensor is discussed in detail in [Section 3.4.1](#). Each measurement is an individual snapshot of an instant and location. Cellular 5G networks, particularly those operating in the n78 band, emit varying levels of electromagnetic radiation due to the highly dynamic nature of data transmission. The combined effects of beamforming, duplexing by way of time-division and highly varying user demand, lead to a high degree of temporal as well as spatial variability of the fields [50-51]. The ICNIRP guidelines suggest a 6-minute average to measure the whole-body exposure related to RF-EMF. However, recent studies suggest that shorter measurement durations can still yield reliable exposure assessments under certain conditions. The Bolte et al. [47] have determined that shorter measurement intervals are adequate for valid RF-EMF exposure assessments for microenvironmental studies. In the study, they made 24-hour personal measurements with exposimeters that sampled at intervals of 10 seconds over different daily activities and environments within the Netherlands. The research revealed that even with the shorter sampling intervals, the measurements reliably captured the variation in exposure levels from different activities, times of day, and locations. This indicates that shorter intervals of measurement, appropriately contextualized, can be valid exposure assessments, especially where the intent is to compare various environments or detect exposure hotspots [47]. Since the drone will conduct multiple exposure assessments, focusing on identifying exposure hotspots and evaluating beamforming, shorter measurement durations of approximately 10 seconds will be used. This approach increases the number of measurements per flight, enabling more extensive data collection across various waypoints because the drone battery remains limited.

To increase the accuracy of your measurements ICNIRP suggests a few points that need to be taken into account [43]:

- Eliminate all nearby transmissions by switching mobile phones off or placing them into airplane mode. This can be done by the operators themselves but other people can't be controlled.
- The measurement is performed in the far-field.
- Eliminate any form of human body interference.
- Avoid large conduction objects near the measuring sensor. Respect at least a distance of 0,5m or more.
- Be aware that the traffic conditions influence the total electromagnetic field that gets radiated. In order to get a good understanding of the maximum electromagnetic field exposure extrapolation needs to be conducted. For the monitoring the average electromagnetic field exposure is the most valuable.
- The sensor needs to employ a true RMS detector and record data. RMS detection accurately captures the total energy content of the signal, including both continuous and pulsed components, providing a true representation of exposure regardless of waveform shape.
- Frequency selective measurements should target a slightly larger frequency band to account for signal leakage, adjacent channel interference and potential frequency drift of real-world transmissions [48].

Lastly it's important to perform an uncertainty assessment. Standard EN 50383 [49] and EN 50413 [50] specify that the expanded uncertainty must not exceed 4 dB at a 95% confidence interval (with an expansion factor of 1.96) for frequencies up to 6 GHz. The Root Sum of Squares (RSS) method is used to calculate the uncertainty, taking into account factors such as calibration (antenna, cable, receiver), mismatch, and repeatability.

1.3.4 Advantages of drone measurements.

Previous RF-EMF exposure assessments primarily used exposimeters, portable devices typically worn on the body to capture spatial and temporal variations in field exposure, or fixed sensors, which remain stationary at a single location for continuous monitoring. Exposimeters are effective for acquiring extensive spatial sampling data. However, their measurement accuracy is compromised due to the perturbative influence of the human body on the electromagnetic field, which introduces increased uncertainty and potential bias in recorded exposure levels [51].

Estenberg et al. developed a vehicle-based measuring system to estimate RF-EMF exposure levels among the general public [52]. Broadband measurements between 30MHz and 3GHz were performed over large areas providing them with a wide variety of average exposure levels in the area. Bolte et al. developed a vehicle-mounted sensor to measure average RF-EMF exposure levels [61]. Electromagnetic shielding involves the use of conductive materials, such as metal, to block or reduce incident radiofrequency signals by reflecting or absorbing portions of the electromagnetic energy. The sensors on these measurement vehicles suffer from antenna anisotropies due to vehicle reflection and alternatively shielding by the vehicle, e.g., the metal parts on the vehicle such as the roof, hood and other body parts act as reflectors of the electromagnetic waves. This can lead to multipath interference, where signals bounce off the vehicle surfaces before reaching the antenna. These reflected signals can either amplify or cancel out the direct signals depending on their phase difference $\Delta\varphi$, creating irregularities in the measured exposure levels.

Isotropic, free-space RF-EMF measurements can be conducted using drone platforms, however in order to ensure accurate exposure measurements, it is essential to characterize and account for potential shielding effects caused by the drone's structural components as well as electromagnetic interference originating from the drone's onboard electronics. Drones enable measurements at various heights and locations with remarkable ease. Unlike heavy spectral equipment mounted on tripods, which is generally constrained to a fixed distance in the far field from the radiation source, drones provide the flexibility to capture exposure levels at different altitudes and in diverse settings. Reflections off surrounding surfaces like structures, vehicles, or other large objects can significantly skew RF-EMF readings by causing multipath effects and constructive or destructive interference. These may result in overestimation or underestimation of the true level of exposure. Through keeping sufficient distance from reflecting surfaces made possible by accurate drone navigation and careful planning of flight routes, such unwanted reflection can be eliminated. In addition to this, flight headings can be planned to avoid flying near metallic or glass surfaces, and measurements can be made over open spaces where line-of-sight conditions predominate, thus enhancing the credibility of free-space exposure measurements.

Apart from enhancing the flexibility of exposure assessments drones provide additional safety in RF-EMF measurements, particularly where high levels of exposure are possible. By providing for remote measurement, drones eliminate the necessity for personnel to be up-close to high-radiation-emission objects during initial surveys. Operators can stay at safe distances to gather preliminary data. Should these initial readings validate that the exposure levels are significantly below the ICNIRP general public limits, additional activity by people in closer proximity may be deemed safe for the public at large. However, if higher levels are detected (approaching or exceeding the general public threshold) any closer measurements must be evaluated under the occupational exposure guidelines, which allow for higher limits but require specific safety protocols and trained personnel.

1.3.5 State-of-the-art of drones for RF-EMF exposure

1.3.5.1 Hexacopter DJI F550 with 3 monopole antennas

The hexacopter used in [53] is created for measuring the RF-EMF exposure from the Global System for Mobile Communications (GSM900) band around 950MHz from 1 to 60m above ground level in a suburban office environment. [Figure 1-13a](#) shows the Hexacopter and [Figure 1-13b](#) shows the measurement environment, where the hexacopter was used. The hexacopter was constructed using the DJI F550 Framewheel kit. It consisted of 6 motorarms, each of them equipped with a brushless DC motor. The flightcontroller was the DJI (type NAZA v2). LiPo batteries from PK Racing, a GPS module, an altitude meter (barometer) as well as a compass were also built on top of the drone. The RF acquisition tools consisted of three lightweight and compact nodes with minimal impact on the battery. The system included a 30 g log detector (ADL5513, Analog Devices), connected to a small monopole antenna through a 20 g SAW filter tuned to the GSM downlink frequency of 942.5 MHz. The output from the detector was fed into a 14-bit ADC, which interfaced with a microcontroller (ATMEGA328) via I2C serial communication. The three (nodes A, B and C) lightweight antennas were placed perpendicular to each other in order to be able to calculate the total electric field. The antennas were of the type ANT GXH615 specifically designed for measurements in the GSM900 band. They have a low reflection parameter S_{11} and are well placed below the drone on plastic holders which limits the drone influence on them [53].

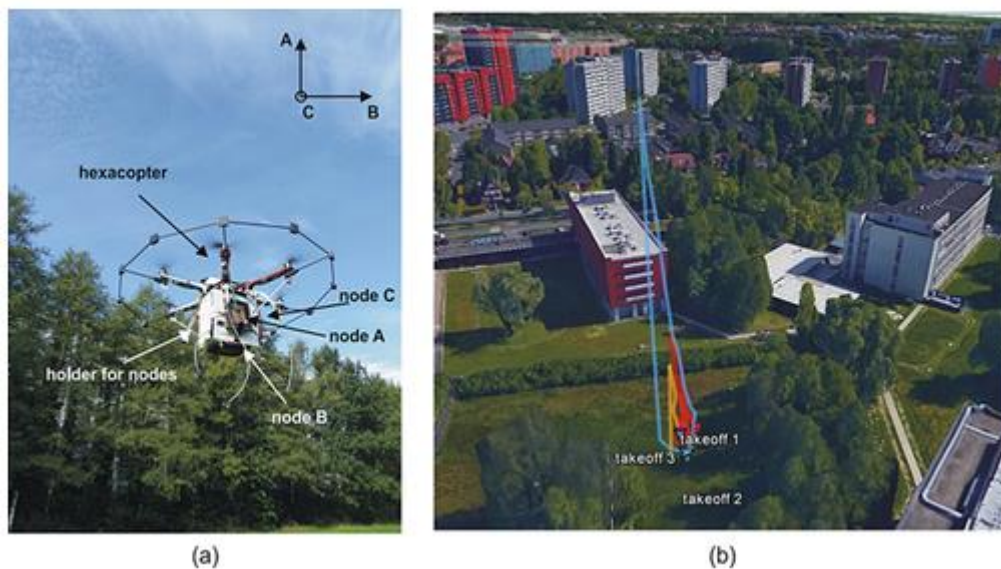


Figure 1-13: Lightweight hexacopter with three identical nodes (A, B and C) for GSM900 measurements (a) [53]

1.3.5.2 Octocopter DJI S1000 with Field Strength Analyzer

[Figure 1-14](#) shows the octocopter used in [54], it is designed using a modified version of the DJI S1000 frame. This frame has eight motorarms and containing eight BLDC motors. It's been successfully immunity tested in the immediate vicinity of 100V/m and is ideal for measuring RF sources such as cellular base stations.



Figure 1-14: DJI S1000 Octocopter with Narda SRM 3006 [54]

The Field Strength Analyzer equipped on the drone is the Narda SRM 3006, supplied by Narda Safety Test Solutions. [Section 1.3.4.3](#) provides more information about this device. This spectrum analyzer contains a microcontroller with an optical interface that communicates to a GCS through a 868 MHz modem with a secure link between the drone and the GCS over long distances. The bandwidth of the connection between the microcontroller and the GCS is not wide enough to send all measurement data real-time, so most of the data is stored on the internal memory of the spectrum analyzer. The data that is transmitted is visualized on a software tool that relies on Python Scripts and Narda Drivers.

1.3.5.3 Octocopter DJI S1000 with an exposimeter

[Figure 1-15](#) depicts the octocopter system employed in the study described in [69]. The research was conducted in the vicinity of a three-story building comprising a ground floor, first floor, second floor, and a rooftop terrace. The objective was to quantify the average RF-EMF exposure around the building and to construct a high-resolution three-dimensional exposure map. A nearby mobile communication site, located approximately 40 meters away on the roof of an adjacent building at a height of 17 meters, hosted antennas operating at multiple frequency bands—specifically 800, 900, 1800, and 2100 MHz. For data collection, the researchers utilized the EME Spy 200 personal exposimeter. This compact and lightweight device is equipped with three orthogonal electric field sensors, enabling isotropic measurements of the electric field strength. The exposimeter continuously records RF-EMF levels across predefined frequency bands within a broad frequency range of 87 to 5850 MHz. It supports flexible sampling intervals between 4 and 255 seconds and offers a storage capacity of up to 80 000 data points, allowing for extensive temporal and spatial exposure profiling [55]. [Figure 1-16](#) shows the results the 3D exposure map around the three-story building. For the aerial measurements they used the DJI S1000 frame. It's assembled with a 6S 16 000 mAh 22.2V LiPo battery, a A2 flight controller, a power management unit (PMU), an inertia measurement unit (IMU) and a GPS module. As remote a DT7 remote controller is used. An autonomous flight of 15 min was achieved with a “return to launch” option in case of a failsafe [69].

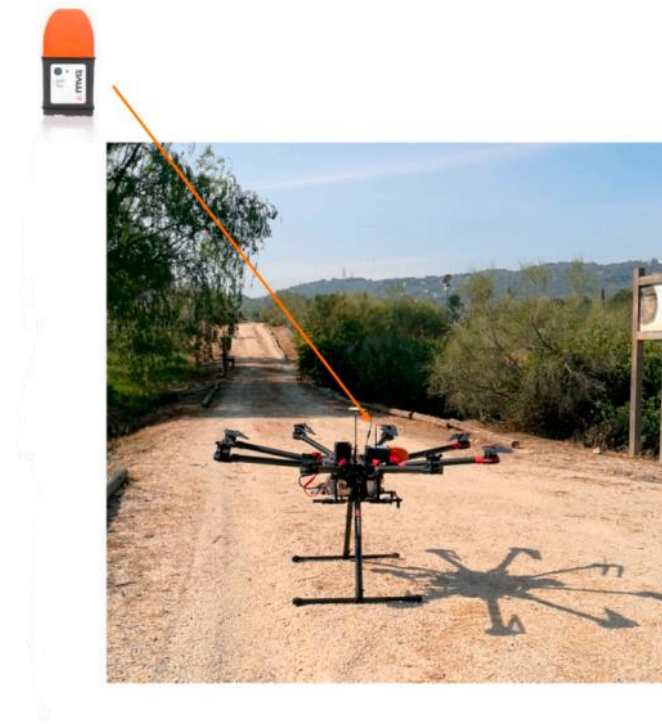


Figure 1-15: DJI octocopter with EME spy 2022 on the drone [69]

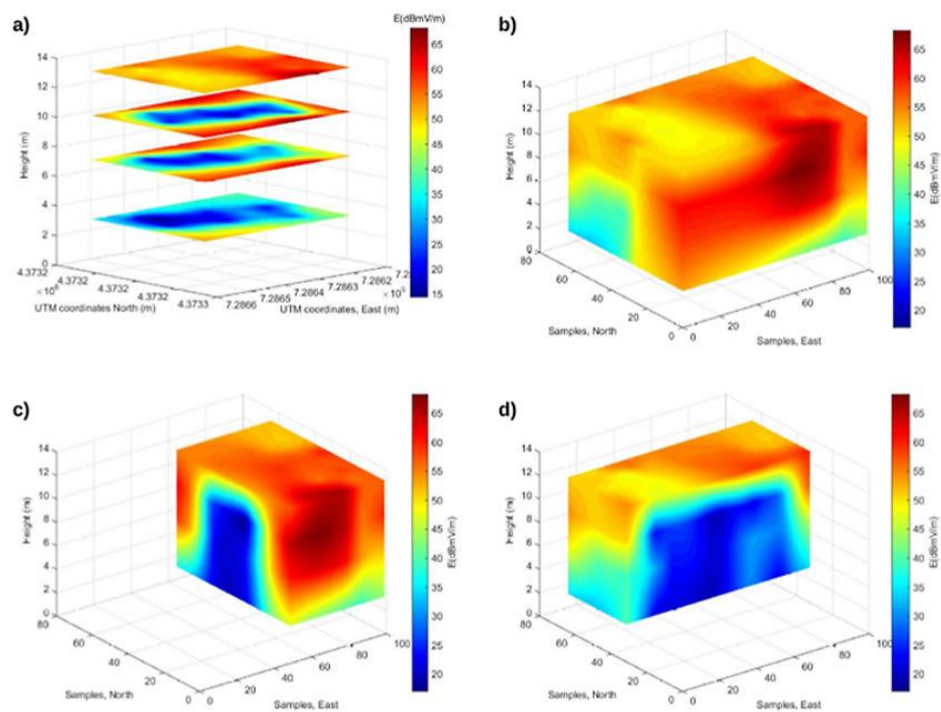


Figure 1-16: 3D RF-EMF exposure maps [69]

1.3.5.4 Quadcopter Drone-g

A research from BRNO University of Technology used a DRONE-G from Nuvia Tech to establish 3D radiation heat map from a point radiation source. [Figure 1-17](#) shows the radiation heat maps in 2D and 3D, illustrating the precision and versatility of drones for RF-EMF assessments [56].

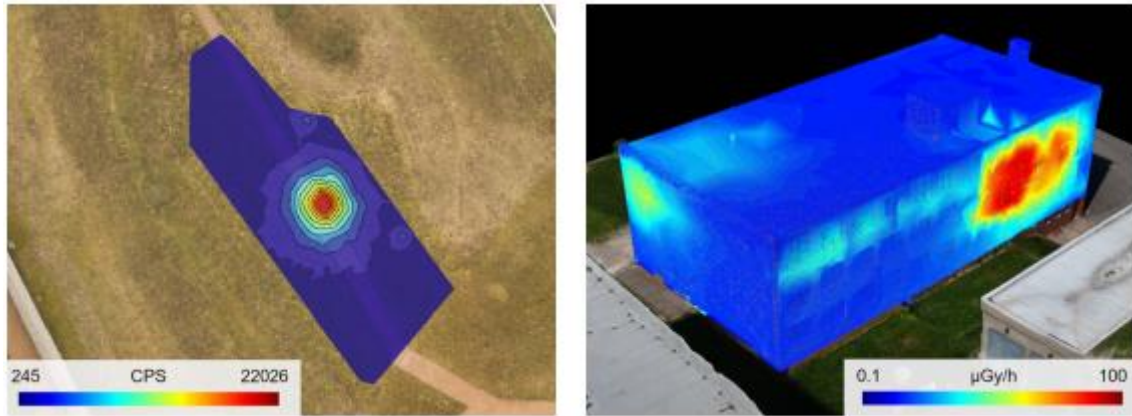


Figure 1-17: A radiation map acquired with an Unmanned Aircraft System (UAS) [56]

2. Research objectives

The objective of this thesis is to establish a vertical 5G NR exposure grid originating from a base station in Ghent. Since flying within 150 meters of an actual base station is prohibited in Belgium, a signal generator with a horn antenna will be used to create a synthetic base station. 5G NR is a new technology and the evolution of its exposure needs to be monitored to track the increase in RF sources (e.g. 5G NR base stations, Wi-Fi routers, smart devices), to address public health concerns and to promote transparency and trust in the deployment of new technologies. In order to establish the vertical exposure grid, several RF-EMF exposure measurements will be taken in various waypoints along a predefined flightpath. These measurements will be taken with a fast-sampling triaxial 5G hardware sensor developed by Van der Straeten et al [57]. The exposure grid will be constructed based on the strength of the electrical field in [V/m]. The measurements will be taken in a full autonomous flight programmed in Python.

To achieve these objectives, a suitable drone must be selected and programmed to fly autonomously along a requested flight path. This necessitates several critical requirements from the drone including the ability to perform a stable outdoor flight, accurate height monitoring and extensive programmability to accommodate the specific mission parameters. A robust failsafe mechanism needs to be integrated, to prevent crashes and ensure safe operation throughout the measurement process.

Additional research is required to evaluate the potential interference caused by the drone's onboard electronic (such as the telemetry system operating at 433 MHz and the RC controller at 2.4 GHz) on the power levels received by the 5G sensor. This investigation aims to identify the extent to which these components contribute to the measured signal. Furthermore, the shielding and attenuation effects of the drone's structural materials must be assessed to quantify their impact on the received signal strength. A comprehensive comparison of the findings will offer valuable insights into the overall influence of the drone on the measurement process, thereby improving the accuracy and reliability of the exposure assessment.

3. Materials and methods

3.1 Drone comparison

To identify a drone that meets all the necessary requirements, five criteria were established to compare and evaluate the available options. The first criterium is size. A smaller drone is more agile, uses less energy, is also less likely to collide with other objects in the environment and is easier to carry around with you. The second criterion is flight duration. A longer flight will create more time to fly waypoints, which results in acquiring more measurements in one flight. The third criterion is the load capacity. The drone will carry a hardware sensor, potentially a UE, a Raspberry Pi and an additional powerbank.

The fourth criterion is programmability. Python contains a wide range of libraries such as matplotlib, keras and pandas, which is useful for calculating and visualizing the measurement results in exposure grids. A precise autonomous flight can be programmed by using a library called Pymavlink. Being able to program the drone in Python is therefore a necessity. The fifth and last criterion is the cost.

3.1.1 The Arduino drone

[Figure 3-1](#) shows an open-source Arduino drone from Carbon Aeronautics [58]. This is a very small drone of 12,5 cm in length, 10 cm in width and 6 cm in thickness. This makes the drone really compact and easy to carry around. A flight duration of approximately 10 minutes is acquired through a 1300 mAh LiPo battery, which is measured through a voltage dividing circuit and a voltage drop over a shunt resistor. The drone can carry a payload of up to 180g. [Figure 3-2](#) shows the flight controller in this Arduino design is a Teensy 4.0, featuring an ARM cortex-M7 core running at 600MHz. It includes 2 MB QSPI flash memory and 1MB of RAM, offering sufficient power for basic control tasks. The Teensy 4.0 has 40 digital Input/ Output (I/O) pins, 31 Pulse Width Modulation (PWM) output pins, 1 analog output, 3 Universal Asynchronous Receiver-Transmitter (UART) pins, 3 Serial Peripheral Interface (SPI) interfaces and 2 Inter-Integrated Circuit (I²C) serial interfaces. It can handle high-speed USB (480 Mbit/s). The drone can be programmed through Arduino IDE software or via Python [58]. The drone is built out of 40 components and they will cost around 235 euro.

The autonomous flight will integrate a depth camera will be used (not in this thesis but in future work). Depth cameras produce large amounts of data, often images of several megabytes in size per frame (especially at higher resolutions and frame rates). This would quickly exceed the available RAM on the Teensy. Even if the resolution is reduced, complex algorithms such as depth mapping, filtering and object avoidance usually require more memory than the Teensy has available. The sensors, depth-camera and the User Equipment (UE) will be too heavy for the drone. These reasons eliminate the Arduino drone.

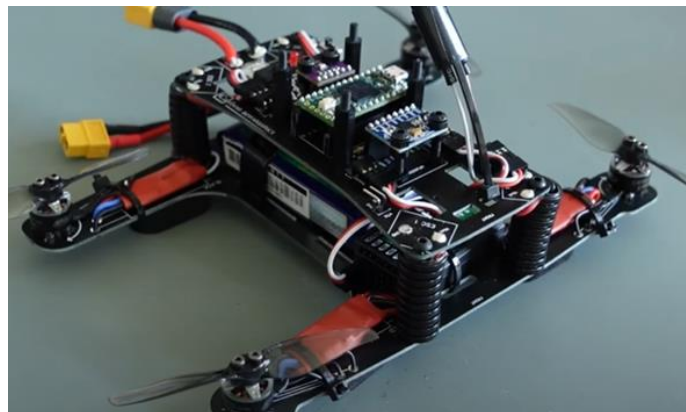


Figure 3-1: Arduino drone [68]



Figure 3-2: the Teensy 4.0 microcontroller [59]

3.1.2 The Holybro Pixhawk drone

[Figure 3-3](#) shows the second drone, which is the Holybro PX4 X500 V2. [Figure 3-4](#) shows the frame, it is a larger drone with a wingspan of 50 cm, a height of 24.3 cm and a thickness of 2.8 cm. The frame's body forms a 144 mm by 144 mm square with a thickness of 2 mm. The landing gear stands 21.5 cm tall, providing sufficient clearance beneath the drone to install the 5G NR sensor. This positioning ensures the sensor is placed well below the quadcopter, helping to reduce the shielding effect. However, some shielding from the sensor mount and landing poles remains unavoidable. The frame is produced in complete carbon-fiber, with newly high-strength and ultra-lightweight 16 mm carbon-fiber tubes, which are designed out of fiber-reinforced nylon connectors or improved plastic tee connectors. The drone has a flight duration of approximately 18 minutes powered by a 4S 3000mAh-5000 mAh LiPo battery and can carry a payload of up to 1500g. It has a dedicated mount for companion computers, such as the Raspberry Pi 4B or the Nvidia Jetson Nano, enabling programming in all languages supported by the companion computers such as C, C++, C#, Python and Arduino are all possible [60].



Figure 3-3: Holybro PX4 X500 V2 drone [60]



Figure 3-4: Holybro PX4 X500 V2 frame [60]

Figure 3-5 shows the Holybro X500 V2's flightcontroller: the Pixhawk 6c. It is powered by a dual-core STM32H7 processor, with a Cortex-M7 as the primary processor and the Cortex-M4 as the secondary. It contains 1MB of flash memory and 512 kB RAM, which is sufficient for running the ArduPilot software (a performant and commonly-used flightcontroller software). The software is lightweight and optimized for drones, focussing on its primary objectives like sensor fusion, PID-control algorithms for a stable flight and navigation. All these tasks require very little memory. More complex functions, such as depth-image processing or route planning can be handled by the companion computer. This allows the Pixhawk to remain focused on its primary task: ensuring a safe and stable flight. The Pixhawk 6C features a redundant Inertial Measurement Unit (IMU) that serves as a backup to ensure accurate measurement of acceleration and rotation in the event the primary IMU fails. It also has a compass for measuring the orientation relative to the Earth's magnetic field during outdoor GPS-based navigation. A barometer will notice changes in the atmospheric air pressure in order to precisely determine the height of the drone for autonomous height control and hovering. Through a power module the battery voltage and current usage is precisely monitored, ensuring a reliable failsafe. For communication, it offers ports like UART for serial communication with telemetry devices, GPS-modules and companion computers, as well as CAN-bus for more robust communication with an RTK GPS or a Lidar. Additionally I²C, SPI and ADC ports can also be used and support less complex external sensors [61].



Figure 3-5: Pixhawk 6C flightcontroller [61]

The integration of a companion computer enhances this drone's versatility and programmability. This allows communication with depth-cameras for advanced functions such as object avoidance and object recognition. The complete sensor fusion setup will be discussed in [Section 3.3.2](#). To verify the drone's payload capacity, the weight of key components is estimated as follows: the 4S LiPo battery weighs approximately 400 grams, the 5G sensor in the mount around 100 grams, the external powerbank around 100 grams and a Raspberry Pi 4B exactly 46 grams. This results in a total weight of approximately 646 grams. Given the drone's payload capacity of 1500 grams, this allows for ample margin. The estimated cost of the drone is 750 euros, which includes the carbon-fiber frame, the motors, the ESC's, the power distribution board, the Pixhawk 6C flightcontroller, the M10 GPS module and a telemetry device. The RC controller is only there for legal compliance, manual intervention and calibration, with only 6 channels being sufficient. The FlySky FS-i6X and iA6B receiver meet these requirements for about 70 euro. A Raspberry Pi 4B adds another 60 euros. In total, the estimated cost for this drone setup is approximately 880 euros, providing a cost-effective solution that meets the necessary requirements. Keep in mind that this price can fluctuate slightly depending on the site, where the drone, the RC controller and the Raspberry Pi are bought.

3.1.3 The DJI S1000 drone

[Figure 3-6](#) shows the final drone model: the DJI S1000. This drone has a wingspan of 104,5 cm and landing gear dimensions of 46 cm in length, 51.1 cm in width and 30.5 cm in height. Its octocopter design, equipped with eight BLDC motors, provides professional aerial photography, cinematography, heavy-lift capabilities, increased stability and redundancy. [Section 1.3.5.2](#) and [Section 1.3.5.3](#) shows two studies where this model was used to measure RF-EMF exposure. If one of the BLDC motors fail, the drone can still maintain flight stability. The design is foldable, which allows for easier transportation. It's completely fabricated out of carbon-fiber, a material known for being both lightweight and strong. The drone is powered by a 6S LiPo battery of 15000 mAh, which provides a flight duration of around 15 minutes. The DJI S1000 is capable of carrying payloads of up to 6600 grams without the battery, making it ideal for heavy-lift operations. The DJI S1000 supports autonomous missions such as waypoint navigation, mapping and surveying, all managed through the DJI Ground Station software. A companion computer can be integrated into the system using the DJI Onboard SDK, offering enhanced programmability and the ability to execute more complex autonomous tasks [62].



Figure 3-6: DJI S1000 drone [62]

[Figure 3-7](#) shows the DJI A3 flightcontroller, which is built with a 32-bit ARM Cortex-M4 processor. It features triple modular redundancy, incorporating three sets of IMUs. This design ensures a stable flight and high reliability. If one or even two IMUs malfunction, it will not result in a crash. The A3 has two GNSS units (Global Navigation Satellite Systems), that support GPS and RTK-GNSS systems. This can achieve centimeter-level accuracy. It can be paired with different multirotor configurations, including the quadcopter, hexacopter or octocopter. For connectivity, the flight controller includes CAN Bus Ports to connect to the DJI Lightbridge 2, which enables the transmission of live HD video at 1080p from the drone's camera to the operator's monitor, with a transmission range of up to 5 km. Additionally, it offers plenty UART ports and PWM ports. DJI is renowned for its advanced flight algorithms, which provide smooth and responsive flight control along with precise altitude hold capabilities [63].



Figure 3-7: DJI A3 flightcontroller [63]

In comparison to other drone models it is not particularly compact even when folded to its smallest form. The flight duration of about 15 minutes is acceptable; however it's worth noting that the Holybro model achieves a 3 minute longer flight consuming only a third of the energy. The load capacity of 6600 grams provides an ample margin to the estimated total weight of 646 grams as discussed in [Section 3.1.2](#). The drone allows for the integration of a companion computer via the onboard SDK, enabling complex autonomous missions through programming. Additionally, the DJI Ground Station, along with the DJI Lightbridge module, can create a real-time exposure grid of the frequency field. However these advanced functionalities come at a cost. The complete setup drone including the frame, motors, ESC's and the A3 flight controller amounts to approximately 1750 euros, In addition to that a more advanced RC controller is required: the FrSky Taranis X9D Plus transmitter, paired with the FrSky X8R receiver, will cost about 260 euros. In total, the estimated cost for this drone setup is approximately 2010 euros.

3.2 The drone selection

Based on the specifications and capabilities of these three drone models: the Arduino drone, the Holybro PX4 X500 V2 and the DJI S1000, the Holybro PX4 X500 V2 is the best choice for conducting research on a vertical exposure grid of 5G NR. The Holybro drone can comfortably carry the required weight, which include the 5G NR sensor, the LiPo battery, an additional powerbank and the Raspberry PI 4B. The total weight is estimated around 646g. This provides ample margin for additional equipment in future work. The DJI drone can carry higher payloads up to 6600 grams but its added complexity is not justified because the Holybro meets the payload requirements adequately. The Arduino drone cannot provide the necessary payload capacity.

The Holybro drone offers the best flight duration of approximately 18 minutes, which is sufficient for covering large areas and conducting thorough 5G NR exposure measurements without the need for frequent recharging. The DJI S1000 offers a 15-minute flight time, but it relies on a 15,000 mAh 6S LiPo battery, three times the capacity of the 5,000 mAh 4S LiPo battery used by the Holybro, highlighting the DJI's comparatively inefficient energy consumption. The Arduino drone has only 10 minutes of flight time, limiting its operational efficiency for extensive data collection.

The programmability of both the Holybro and the DJI drones is comparable because they both support the same companion computers. However the DJI drone supports the DJI Lightbridge 2 module, which creates the opportunity to draw a real-time exposure grid. The autonomous capabilities between the two are almost identical. Both ArduPilot's MissionPlanner and the DJI Ground Station Software support the same functionalities. ArduPilot's open-source software does contain a lot more documentation online. In contrast the Arduino drone lacks the necessary processing power and memory to handle complex algorithms required for effective autonomous operation.

The Holybro costs approximately 880 euros providing a sustainable, cost-effective solution for all the requirements. It supports all essential components for the autonomous measurements without excessive expenditure. Conversely, the DJI drone costs approximately 2010 euros, and this higher cost does not translate into a proportional increase in capabilities. While the Arduino drone is the most affordable option at 235 euros, it fails to meet the required specifications.

3.3 The assembly

3.3.1 Full mechanical design

[Section 3.1.2](#) already highlighted most of the mechanical design parts but in order to create a solid understanding of all the used parts, they are all briefly repeated here. The framework is based on the X500 V2 Frame kit. The body consists of a full carbon-fiber top and bottom plate with dimensions of 144 x 144 mm and a thickness of respectively 2 mm and 1.5 mm. The four full-carbon fiber motor arms with a diameter of 16 mm are positioned at the corners, securely placed between the carbon fiber top and bottom plates. The landing gear consists of four poles, two vertical poles with a diameter of 16 mm made in full carbon-fiber and two horizontal poles with a diameter of 10 mm. They are connected to each other with engineering plastic and some screws and the horizontal poles hold some foam to absorb oscillations while landing. Underneath the bottom plate two mounting rails with a diameter of 10 mm and a length of 250 mm are connected to a battery mounting board with two battery straps. These are built for 3300 mAh or 5000 mAh LiPo batteries. There is a 3 mm black silicone sheet attached towards the battery mounting board to create a smooth assembly between the battery and the mounting board. Then on the back of the drone there is a platform board with mounting holes for GPS and a popular companion computer like a Raspberry Pi. This is also fabricated in carbon-fiber. [Table 3-1](#) shows complete list of all the mechanical items in the list. [Figure 3-8](#) shows all mechanical parts labelled per group [64].

Table 3-1: Holybro X500 V2 mechanical parts list

Item	Description	Quantity
Bottom plate	Carbon fiber (2 mm thick)	1
Top plate	Carbon fiber (1.5 mm thick)	1
Arm	Carbon-fiber tube (assembled with motors mounted)	4
Landing gear - vertical pole	Carbon fiber tube + engineering plastic	2
Landing gear - cross bar	Carbon fiber tube + engineering plastic + foam	2
Mounting rail	Diameter: 10mm length: 250mm	2
Battery mounting board	Thickness: 2mm	1
Battery pad	3mm Silicone sheet black	1
Platform board	Thickness: 2mm	1
Hanger & rubber ring gasket	Inner hole diameter: 10mm black	8

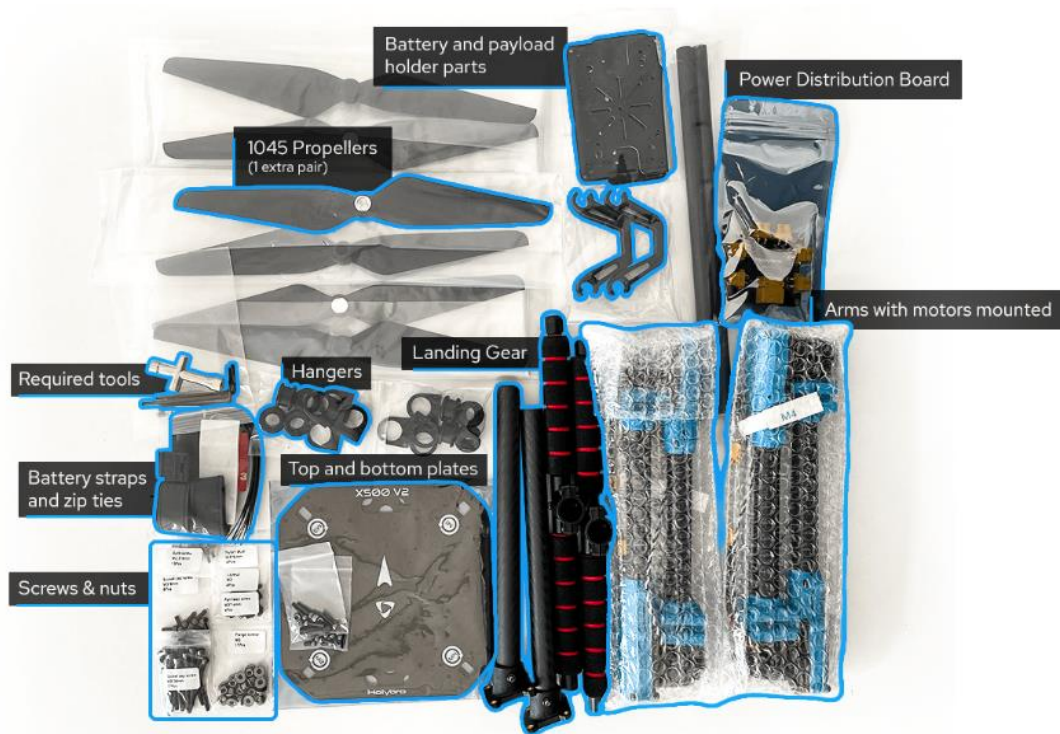


Figure 3-8: Holybro X500 V2 ARF kit mechanical parts labelled per group [64]

The triaxial 5G sensor needs to be protected between the drone's landing gear poles in order to protect it against potential crashes or other drone malfunctions. A 3D CAD mount was designed in Siemens NX and 3D printed in PLA. [Figure 3-9](#) shows the sensor mount. Within the middle part of the mount the triaxial sensor will be screwed tight with 3 plastic bolts and 3 plastic nuts. The sensor is raised to a height of 20 mm above its reference level (lowest left corner at $X = 0$, $Y =$ and $Z = 0$) because the Y-antenna has a vertical displacement of 13 mm down.

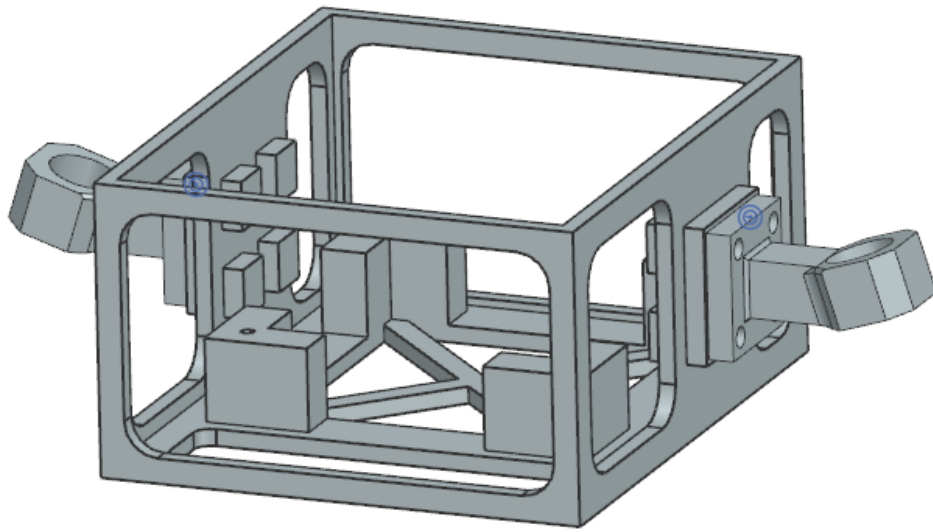


Figure 3-9: CAD mounting part for triaxial 5G sensor

[Figure 3-10](#) shows the total mechanical assembly in Siemens NX. The sensor mount is placed as far as possible from the four motors to decrease possible Electromagnetic Interference (EMI) and reduce the vibrations coupled to the sensor.

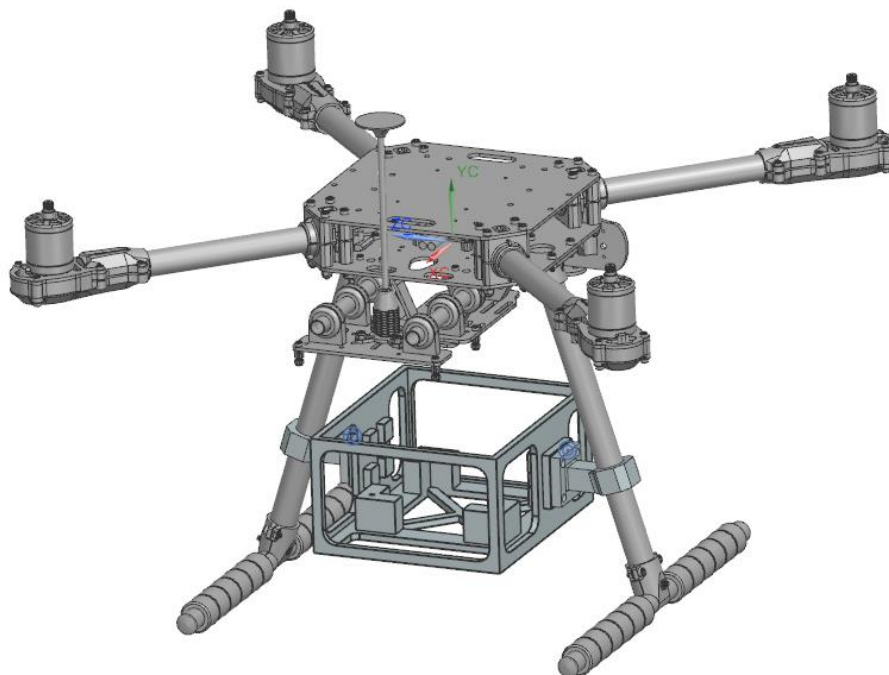


Figure 3-10: Full Holybro X500 V2 mechanical assembly

3.3.2 Full electrical assembly

The electrical assembly contains a series of electronics, which all form a sensor-fusion EKF3 system. The flightcontroller is the Pixhawk 6C. This is the central neural system of the drone and contains several electronic components. At the heart of the Pixhawk 6C is an STM32H743 microcontroller. This high-performance ARM Cortex-M7 processor, running at 480 MHz, is responsible for executing the flight control algorithms, processing sensor data, and managing communication interfaces. The microcontroller features a floating-point unit (FPU) and a digital signal processor (DSP) to enhance computational efficiency, making it suitable for real-time applications. The Pixhawk 6C integrates a dual IMU system to ensure redundancy and enhance flight stability. The primary IMU consists of high-precision accelerometers and gyroscopes: the BMI088, a 6-axis motion sensor with low noise and high stability, used for precise motion detection and the ICM-42688-P, a high-performance 6-axis IMU with improved temperature stability and low drift characteristics. The onboard magnetometer is the IST8310 is used for heading estimation. It measures the Earth's magnetic field to determine the drone's orientation relative to magnetic north. It also contains the MS5611 a high-resolution barometric pressure sensor. It measures the atmospheric pressure to determine the altitude. All flights are logged and stored on a microSD card. The Pixhawk has several communication interfaces such as the UART for telemetry devices, I²C for external sensors, CAN for LiDAR sensors or UAVCAN devices, SPI for high-speed sensors and PWM modules to control the motors. The UART connection will be used to establish a serial communication between the Raspberry Pi 4B and the Pixhawk 6C using the MAVlink 2 protocol. [Table 3-2](#) shows a brief overview of all the sensors that are integrated in the Pixhawk 6C [61].

Table 3-2: Pixhawk 6C internal electronics

Function	Component
Microcontroller	STM32H743 with ARM Cortex-M7
IMU[0]	BMI088
IMU[1]	ICM-42688-P
Magnetometer	IST8310
Barometer	MS5611
Communication protocols	UART, I ² C, CAN, SPI and PWM

The 5000mAh 4S LiPo battery distributes power through the PM02D power module, which has two outputs. The first provides a stable 5V regulated supply to safely power the flightcontroller, while the second connects to a power distribution board (PDB). The PDB features four pre-soldered ESC power connectors, supplying power to the Holybro BLHeli S ESCs, which support a peak current of 20A and operate with an internal MOSFET switching frequency of 30kHz. Each ESC drives a 2216 KV880 brushless motor, where the KV rating of 880 indicates that the motor spins at 880 RPM per volt applied. With a 4S LiPo battery (14.8V), the theoretical maximum speed is 13.024 RPM. However, due to voltage sag, aerodynamic drag, ESC efficiency losses, and back-EMF limitations, the actual in-flight RPM generally remains below 10.000 RPM. The motors draw a continuous current of approximately 15-20A, corresponding to a power consumption of 222-296W per motor, though this peak usage occurs only briefly. The ESC's receive PWM control signals from the flightcontroller's main output module, typically operating at 400Hz to 490Hz for multirotor applications. Internally, the ESCs use trapezoidal commutation, synchronized with their 30kHz MOSFET switching frequency to efficiently drive the motors [65]. [Figure 3-11](#) shows a complete connection of the power circuit can be observed.

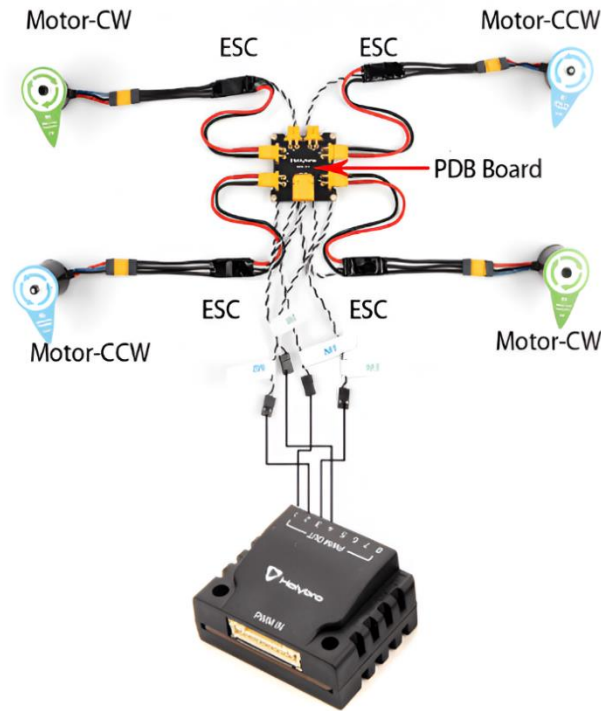


Figure 3-11: Electrical power distribution circuit [65]

Figure 3-12 shows all connections with the flightcontroller. During testing and in compliance with regulations, it is required that the drone is always connected to a controller, even during automatic flights. The FlySky FS-i6 controller is used for this purpose, which communicates with the FlySky-i6AB receiver on a 2.4 GHz frequency. The impact of this communication on the 5G sensor will need to be quantified. For communication between the Pixhawk and the receiver, the SBUS RC pin is utilized. The M10 GPS is responsible for acquiring the drone's position and is connected to the GPS1 pin. It has a typical accuracy of approximately 4.5 meters, meaning that the actual position of the drone is within a 4.5-meter radius with 95% certainty. The telemetry device operates on a 433 MHz frequency to communicate with the GCS. It is connected to the TELEM1 pin on the Pixhawk. The GCS is a laptop with another 433 MHz telemetry device connected via USB, enabling flight information to be transmitted from the drone to the GCS, where it is visualized using Mission Planner. The Raspberry Pi 4B is connected to the TELEM2 port via its TX, RX, and GND pins, and it communicates serially using the MAVLink 2 protocol. The 5G sensor is powered by the Raspberry Pi 4B. The Raspberry Pi 4B is powered by an additional 2200 mAh power bank. It is not safe to power the Raspberry Pi 4B through the flight computer because drawing too much power from it could lead to permanent damage. This also does not provide a sustainable or reliable solution. Table 3-3 shows all components connected to the flight controller and the connection/communication protocol that they utilize to communicate.

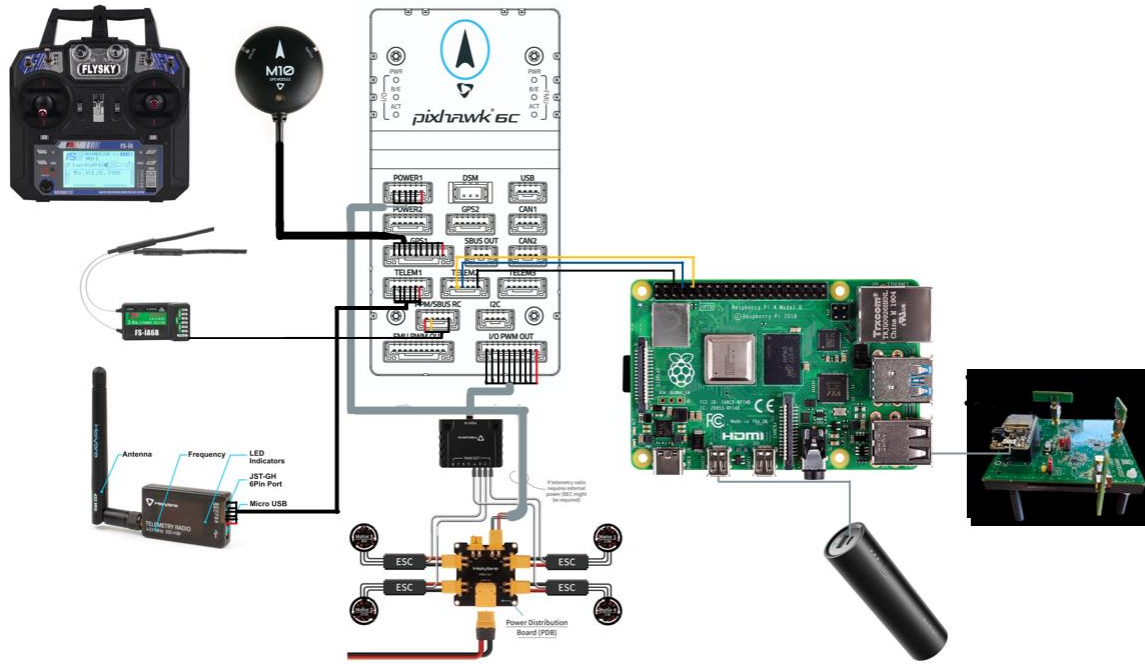


Figure 3-12: Full electronic connections

Table 3-3: All electronics communicating with the flightcontroller

Item	Description	Connection/communication
FlySky FS-i6	RC controller	2.4 GHz with the FS-iA6B
FS-iA6B	RC receiver	SBUS RC pin
M10	GPS	GPS1 pin
Telemetry radio 100mW	GCS communication and control	TELEM1 pin and 433MHz broadcast
Raspberry Pi 4B	External computer	TX, RX and GND through TELEM2
Triaxial 5G sensor	5G sensor	USB

3.4 The triaxial sensor 5G sensor

3.4.1 Characteristics and design

[Figure 3-13](#) shows the triaxial 5G NR sensor, which is mounted on the drone, designed by Van der Straeten et al [57]. The sensor contains three dipole antennas, which are positioned perpendicular to each other. They resonate at 3.86 GHz and have a -10 dB bandwidth of 800MHz. The signal is first passed through a multilayer bandpass filter before being measured by the RMS power detector. The voltage at the output of the RMS detector is a linear-in-dB representation of the received RF power signal. The RMS power detector can measure power between the range of DC and 3.9GHz while having a dynamic range between 62 dB and 68 dB. The lower detector limit ranges between -60 dBm and -57 dBm, which correlates with an analog output power between 0.32V and 0.25V. Minimum, maximum and average measured RMS power per channel are calculated by the ESP32 microcontroller. The architecture of the sensor contains 5 tasks: SensorConfig, CreateInterrupts, spiReadData, convertData and sendTask. During the convertData task the powers are calculated based on a lookup table and then they are transmitted and stored during sendTask process [57].

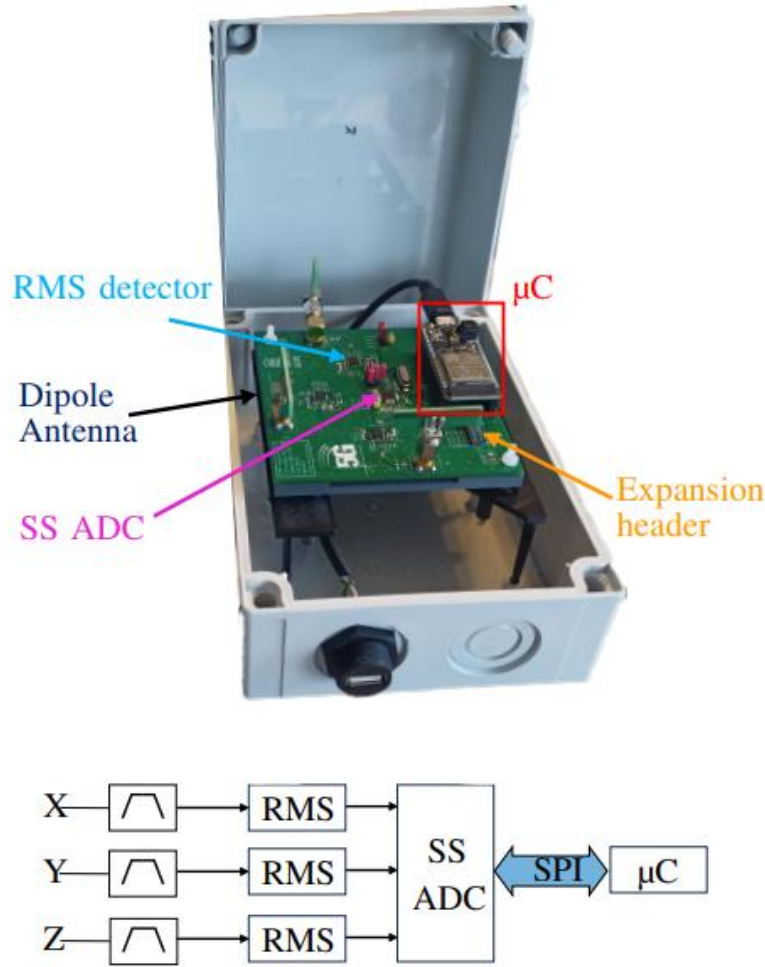


Figure 3-13: the triaxial 5G sensor [57]

The sensor achieves a sample rate of 25kSps at a resolution of 16 bits. This corresponds to a total data throughput of 400 kbit/s. The sensor has been through three calibration processes: an onboard calibration, a free-space calibration and a frequency verification. During the onboard calibration the antennas were replaced by 50 Ω terminations and each channel, one at a time was connected to the a calibrated signal generator (the SMB100A manufactured by Rohde & Schwarz) to determine the output voltage of the RF detector as a function of the incident power. The output was swept from -70 dBm to 8 dBm in steps of 1 dBm at a fixed frequency of 3.625 GHz. With that experiment the noise floors were determined: $P_{x,NF} = -55.73$ dBm, $P_{y,NF} = -57.73$ dBm and $P_{z,NF} = -60.73$ dBm and the lookup table was constructed for each axis [57].

During the free-space calibration of the sensor. The triaxial sensor was mounted on a tripod, which was placed on a calibrated turn table (model TT 0.8 PF manufactured by Maturo GmbH). Then a signal of 3.625 GHz was transmitted to the sensor. The sensor was placed at a height of 1.5 m and at a distance of 2.0 m from the transmit antenna. The setup was constructed in a semi-anechoic chamber. After each measurement the triaxial sensor was replaced by an isotropic frequency-selective EMF field strength analyser (the SRM-3006). This concluded that the noise floor of the sensor was 0.06 V/m and that the average E-field value reported by the triaxial sensor was within 3 dB of the E-field value reported by the SRM, which was within its uncertainty range of 3 dB. By calculating the total uncertainty, keeping into account the uncertainty of the calibration device ± 3 dB, the uncertainty of the RMS power detector of ± 0.5 dB and an underestimation of 5.1 dB or overestimation of 3.8 dB caused by anisotropies. This resulted in an combined uncertainty error u_c of 3.12 dB [57].

3.4.2 Onboard electronics influence experiments

To determine the individual contributions of onboard electronics (including the BLDC motors, ESCs, telemetry radio at 433 MHz, RC receiver antenna at 2.4 GHz, and Raspberry Pi) to the RF-EMF exposure measurements, a series of experiments will be conducted. The "onboard electronics" also include the electromechanical BLDC motors, which may influence the sensor readings through both mechanical vibrations and potential electromagnetic interference (EMI). The high-frequency switching and substantial currents in the stator windings can generate EMI, while rotational imbalances may introduce mechanical noise, both of which can affect RF-EMF measurements. In these experiments, each onboard electronic component will be activated both individually (e.g., telemetry radio alone, RC controller and receiver alone) and in selected combinations (e.g., telemetry radio with BLDC motors, telemetry radio with RC connection) to evaluate their individual and combined impact on the received power P_r as measured by the triaxial 5G sensor. These experiments will be divided into two measurement campaigns. [Figure 4-4](#) presents the first measurement campaign, in which the triaxial 5G sensor is mounted facing upward, orienting all three antennas toward the LiPo battery. In contrast, [Figure 4-5](#) shows the second campaign, where the sensor is mounted facing downward, positioning all antennas toward the ground during flight. Both measurement campaigns will conduct similar experiments, allowing for a comparison that helps define the sensor orientation (upward or downward), which minimizes influence by the onboard electronics. The goal of these experiments is twofold: to determine the optimal sensor orientation and to quantify the influence of each electronic device individually. Each experiment will be represented on a summary chart (a separate chart for the two campaigns), showing the average received power level for each axis, $P_{i,avg}$, over a 30-second period. To aggregate the power values, their logarithmic nature will be considered. Additionally, the IA6B RC receiver antennas will be rotated independently to assess orientation-dependent shielding effects. Antennas positioned above the carbon-fiber frame (comprised of conductive yet lossy dielectric material) may experience reduced P_r due to partial electromagnetic shielding. Carbon-fiber reflects and absorbs incident RF energy, acting as a partial Faraday cage, especially at 2.4 GHz. This effect attenuates RF field strength reaching the sensor and may contribute to lower measured exposure levels.

3.4.3 Shielding experiment

The mechanical structure of the drone, including its four motor arms, landing gear poles, sensor mount and propellers may introduce a shielding effect, which refers to the attenuation of the incident electromagnetic power. Such structural elements can distort the local electromagnetic field and reduce the power received P_r by the onboard sensor. To accurately quantify this shielding effect a series of controlled shielding experiments will be conducted in a semi-anechoic chamber in the lab, focusing on the centre frequencies used by major 5G service providers operating within the n78 band in Belgium. [Figure 3-14](#) shows the experimental setup. The drone is placed at a height of 0.84 m on a motorized turntable (model TT 0.8 PF from Maturo GmbH). A TX antenna is positioned 1.50 m away at a height of 1.84 m and emits continuous wave signals at 3.455 GHz, 3.530 GHz, 3.650 GHz, and 3.750 GHz, with transmission power levels of 15 dBm and 18 dBm. The 1.0 m height offset between the TX antenna and the drone simulates realistic deployment conditions, where the base station antenna is typically elevated relative to the drone during low-altitude flight. This is also more relevant because this represents the exposure directed towards people. During each test, the drone is rotated counterclockwise for 3 minutes at an angular velocity of $2^\circ/\text{s}$, followed by a clockwise rotation for another 3 minutes with a mechanical delay between the two rotations of 1s. These 8 experiments (2 attenuations for each centre frequency) are then repeated with only the triaxial 5G sensor placed at the same height and distance from the TX antenna, ensuring identical conditions. By comparing the received power levels at identical frequencies and attenuations with and without the drone, the shielding effect at angles induced by the drone's structural components can be quantitatively assessed,

without misattributing directional sensitivity or frequency-dependent anisotropies inherent to the sensor itself.

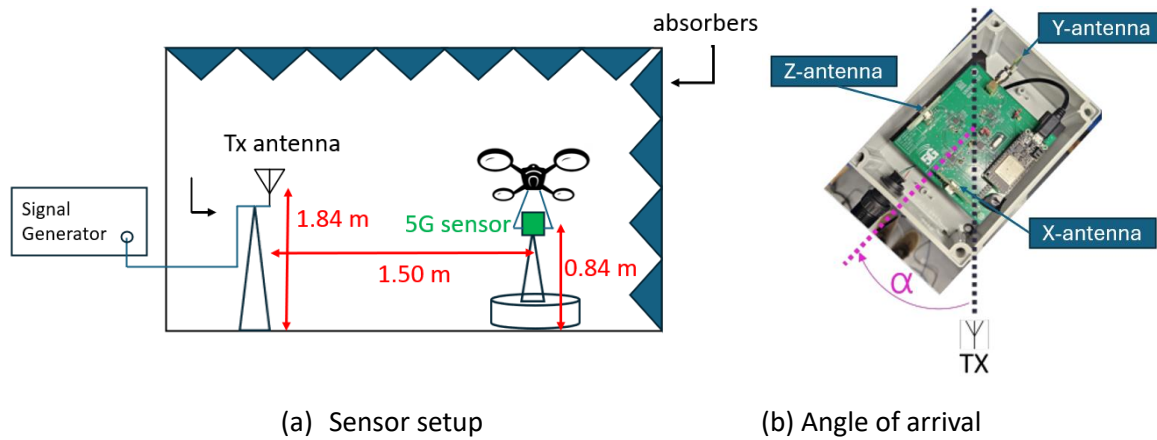


Figure 3-14: The triaxial 5G sensor is mounted on the drone and positioned on a motorized turntable at a height of 0.84 m, located 1.5 m from the TX antenna. The TX antenna is fixed on a tripod at a height of 1.84 m. To isolate the influence of the drone structure, the same set of eight experiments is repeated with the 5G sensor alone, placed in the identical position and orientation. (a) The angle of arrival α indicates the relative orientation between the sensor and the transmitter. (b) [57]

3.4.4 Free-space calibration

Figure 3-15 illustrates the free-space calibration procedure. In this setup, the drone and triaxial 5G sensor are replaced with a calibrated field strength analyzer (Narda SRM-3006), positioned identically to the sensor location used during the shielding experiments described in Section 3.4.3. The SRM-3006 is mounted at the same height and distance from the TX antenna and is rotated at a constant angular velocity of $2^\circ/\text{s}$ (first clockwise for 3 minutes, then counterclockwise for another 3 minutes) completing a full 360° sweep in both directions. During this 6-minute measurement cycle, the SRM-3006 records the time-averaged electric field strength at four distinct centre frequencies (3.455 GHz, 3.530 GHz, 3.650 GHz, and 3.750 GHz), each tested at two different attenuation levels (15 dBm and 18 dBm). These measurements serve as a reference under ideal free-space conditions, free from structural interference or scattering. By comparing the received power values from the 5G sensor equipped on the drone in the shielding experiments to those obtained with the SRM-3006 during this calibration, the antenna factor (AF) of the 5G sensor can be determined as a function of frequency. The AF accounts for the frequency-dependent response of the sensor and enables accurate conversion between measured voltage (or received power) and the incident electric field strength, improving the reliability of subsequent RF-EMF exposure assessments.

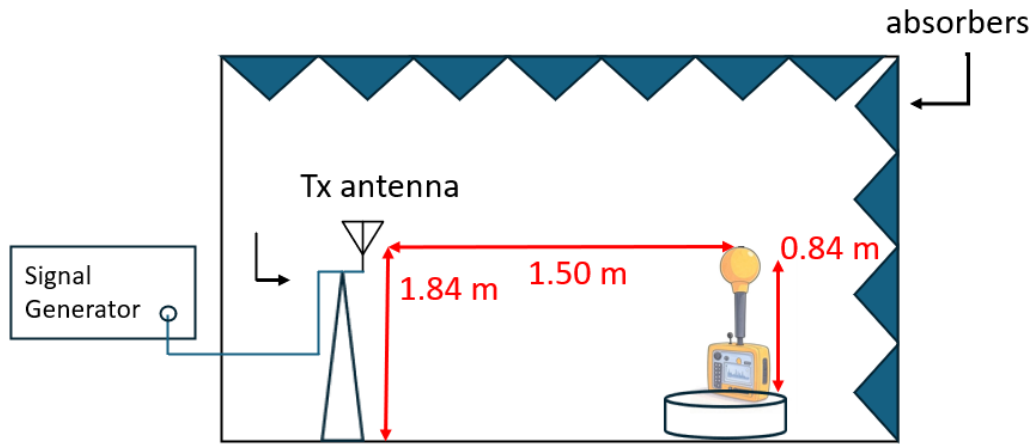


Figure 3-15: The free space calibration setup; The drone is swapped for the SRM 3006.

3.5 The drone calibration

Tuning a copter refers to the process of optimizing the parameters of its flight control system (typically a Proportional-Integral-Derivative (PID) controller) to achieve stable, responsive, and efficient flight. This involves adjusting control loop gains and related settings to ensure accurate response to pilot commands or autonomous inputs, while minimizing undesired behaviours such as oscillations, drift, or latency. Effective tuning aligns sensor feedback (e.g., gyroscopes, accelerometers) with motor outputs, allowing the vehicle to maintain controlled flight across a range of conditions and manoeuvres. Inadequate tuning can lead to instability, poor performance, and unpredictable behavior, which may result in excessive vibrations, reduced responsiveness, or difficulty maintaining altitude and control factors that increase the risk of crashes. For autonomous operations, precise tuning is critical to ensure reliable, smooth, and safe flight. For the drone calibration the methodic configurator was used. This contains about 50 steps to tune any copter from scratch and includes different calibrations and test flights. The results of these will be stored in the memory of the flight controller in the form of parameters [66].

3.5.1 IMU calibration

IMU temperature calibration reduces the probability of Accel inconsistent and Gyro inconsistent errors and reduces the time required to arm the vehicle. IMU temperature calibration requires lowering the temperature of the autopilot (flight controller) to circa -20°C . That is harder to do once the flight controller is assembled on the carbon-fiber top plate, hence it is done in the beginning of the tuning process. The IMU calibration process includes placing the flight controller without battery in a freezer capable of reaching the vehicle's minimum expected operating temperature (-18°C for the freezer used). Then the flight controller is powered and shouldn't be moved while performing the temperature calibrations. This temperature calibration will reduce initialization time because sensor outputs are closer to nominal values at startup and improve the gyro and accelerometer reliability across a wide temperature range, enhancing overall flight stability and control.

[Figure 3-16](#) shows the temperature calibration for the gyros from IMU0 and IMU1. Each plot shows uncorrected and corrected angular rate readings (gyro drift) on the left Y-axis in $^{\circ}/\text{s}$. This is done for each axis of the gyroscope. On the X-axis the time in $[\text{min}]$ is displayed. On the right Y-axis the temperature in $^{\circ}\text{C}$ is displayed. While the time progresses the temperature is gradually increased inside of the flight controller. Before temperature calibration the outputs from IMU[0] show significant temperature-induced drift, particularly on the X and Y axes.

- The uncorrected X-axis drift increased up to 0.4 °/s from 0°C up until 30°C before decreasing again.
- The uncorrected Y-axis drift decreased up to -0.6 °/s at around 40°C.

IMU[1] showed significantly less gyroscope drift. After the temperature calibration was done all gyro drift remained between 0.05 °/s and -0.05 °/s for IMU[0] and IMU[1].

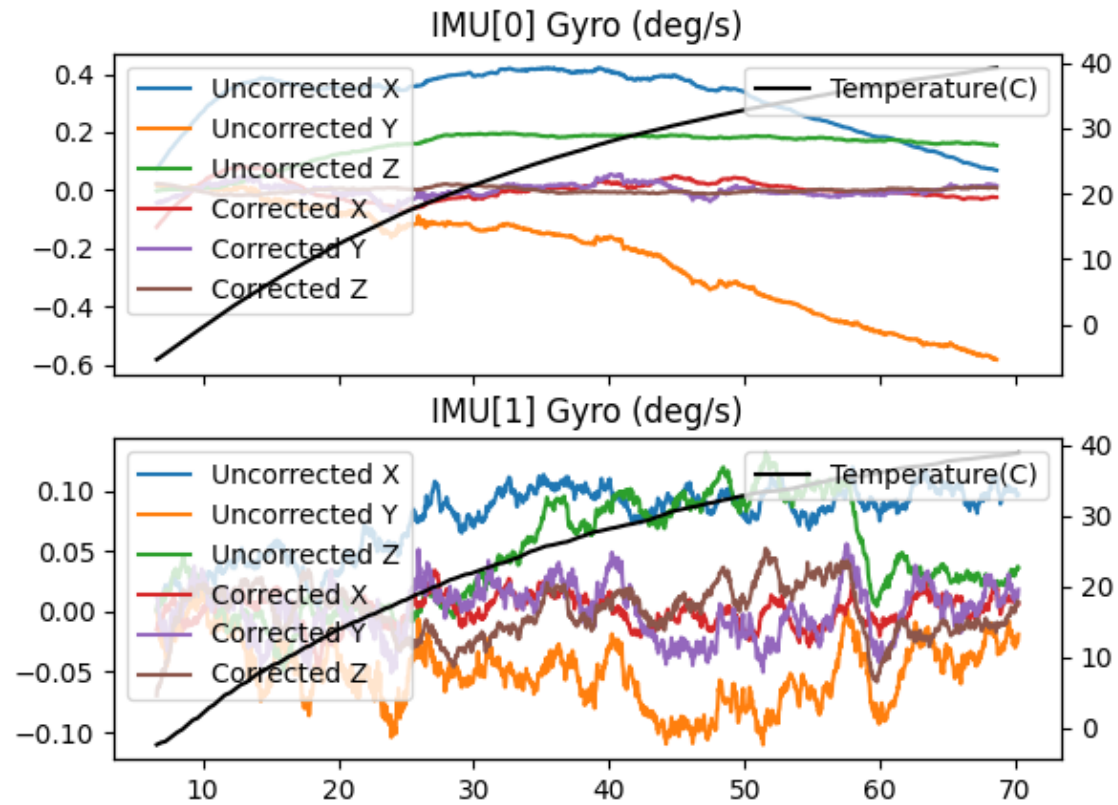


Figure 3-16: Gyro IMU[0] and IMU[1] calibration

Figure 3-17 shows the temperature calibration for the accelerometers from IMU0 and IMU1. The only difference between this plot and the previous gyroscope plots is that now on the left Y-axis the accelerometer drift in [m/s²] is displayed instead of the angular drift. While the time progresses the temperature is gradually increased inside of the flight controller. Before temperature calibration the outputs from IMU[0] showed low temperature-induced drift. IMU[1] on the other hand showed significant temperature-induced drift particularly on the X and Z axes.

- The uncorrected X-axis drift initialized at -0.2 m/s² at 0°C.
- The uncorrected Z-axis drift initialized at 0.3 m/s² at 0°C.

After the calibration all accelerometer drift remained between -0.02 m/s² and 0.02 m/s² for IMU[0] and IMU[1].

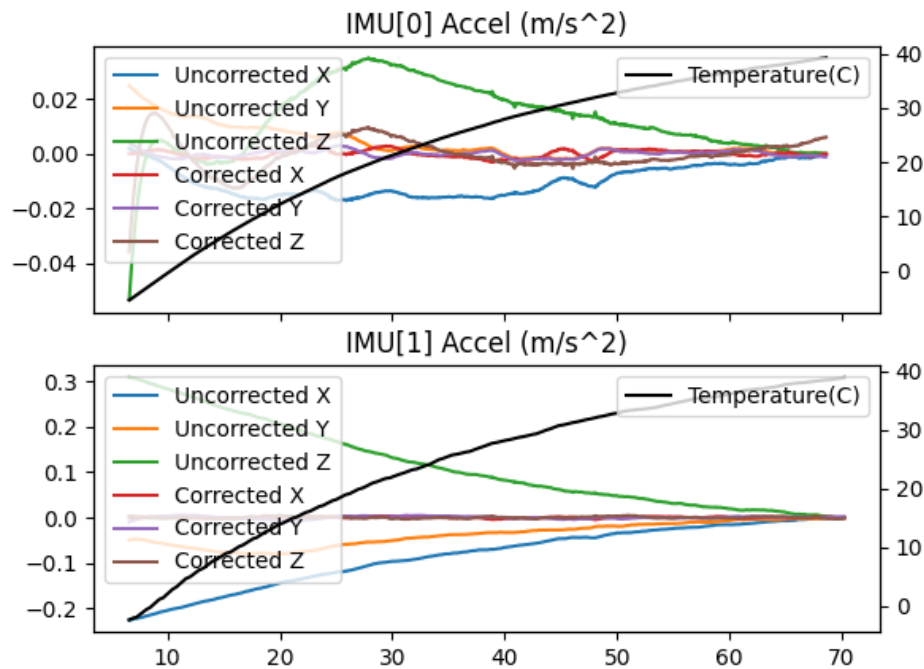


Figure 3-17: Accelerometer IMU[0] and IMU[1] calibration

3.5.2 Accelerometer calibration

[Figure 3-18](#) shows the accelerometer calibration when the flight controller was pointed nose down. During this calibration the minimum and maximum gravitational acceleration values along the three axis (X, Y and Z) are defined. In order to perform this calibration the flight controller is placed in six different orientations to record the extreme values for each axis. These values help determine the scale and range of the sensor readings. To define these extreme values the flight controller is placed on each of its six edges: levelled, upside-down, nose down, nose up, on the left side and on the right side. Aside from that even when the flight controller is placed perfectly levelled, small sensor biases can cause readings to be slightly off. These offsets (bias values) need to be corrected so that the accelerometer correctly registers “zero” tilt when the flight computer is truly levelled. The Attitude and Heading Reference System (AHRS) uses the accelerometer along with gyroscope data in order to carefully estimate the aircraft's orientation. If accelerometers include small errors, these errors might cause the AHRS to think that the aircraft is slightly tilted when it is in fact levelled. To correct these inaccuracies, a number of trims are used, which makes certain that the AHRS accurately identifies a level position when the drone is actually levelled.



Figure 3-18: Accelerometer calibration: nose down

3.5.3 Radio calibration

In order to guarantee that your flight computer correctly interprets the input received from its RC controller, a radio calibration must be performed. This process determines the maximum and minimum PWM values of the RC controller's sticks, allowing the flight controller to accurately map pilot commands for aircraft movement. In calibration, the pilot moves all of the control sticks (roll, pitch, yaw, and throttle) to extreme positions. MissionPlanner (the primary software from ArduPilot) is used to record these extreme PWM values and marks them with red lines in the software. [Figure 3-19](#) shows visual red lines, which indicate the detected PWM input range for certain movements. A radio that is not set up properly may cause the flight controller to misunderstand the stick commands, possibly leading to important flight issues such as: diminished accuracy in response, unexpected motions and in the worst case crashes.



Figure 3-19: Radio calibration for Roll, Pitch, Throttle, Yaw, Radio 5 and Radio 6

3.5.4 Compass calibration

The Pixhawk 6C comes with the IST8310 internal compass but this compass has more potential to interfere with the other internal electronics, that's why using the external IST8310 compass built in the M10 GPS module is a more reliable alternative. Therefore the external compass was selected as the first priority and the internal as the second priority. For the compass calibration the compass needs to be spun in each orientation for approximately one minute. It's important to do it away from magnetic fields or large bits of metal. During the compass calibration the flight controller collects magnetic field data from different orientations. Internal components (wiring, motors, and power distribution boards) can create magnetic disturbances that affect the compass. By analysing how the sensor behaves in different orientations, the system can estimate and correct for hard iron distortions (caused by permanent magnetic fields inside the drone). During a flight a common phenomenon known as the "Toilet Bowl" effect creates a slow, circular drifting motion when trying to hold position. This is a strong indication of a poorly calibrated compass. [Figure 3-20](#) shows the compass attached to the flight computer in order to perform the compass calibration. Both arrows point in the same direction indicating the front of the drone.



Figure 3-20: External compass calibration

3.5.5 Notch filter setup

A harmonic notch filter is a specialized signal processing tool employed in drone flight control systems to attenuate specific frequency components, particularly those associated with mechanical vibrations. By targeting and suppressing these frequencies, the detrimental effects of motor-induced vibrations on the IMU readings are mitigated [67]. In order to configure this notch filter a test flight needs to be performed, where the drone hovers for at least 30 seconds in the mode althold (the altitude of the drone remains constant but the roll, pitch and yaw can still be controlled via the RC controller) or in loiter (the altitude, yaw, pitch and roll of the drone are all constant). [Figure 3-21](#) shows a snapshot of the flight, where the drone hovered at different waypoints at different altitudes. The drone hovered for about 40 seconds at each altitude varying from 2m up until 5m.

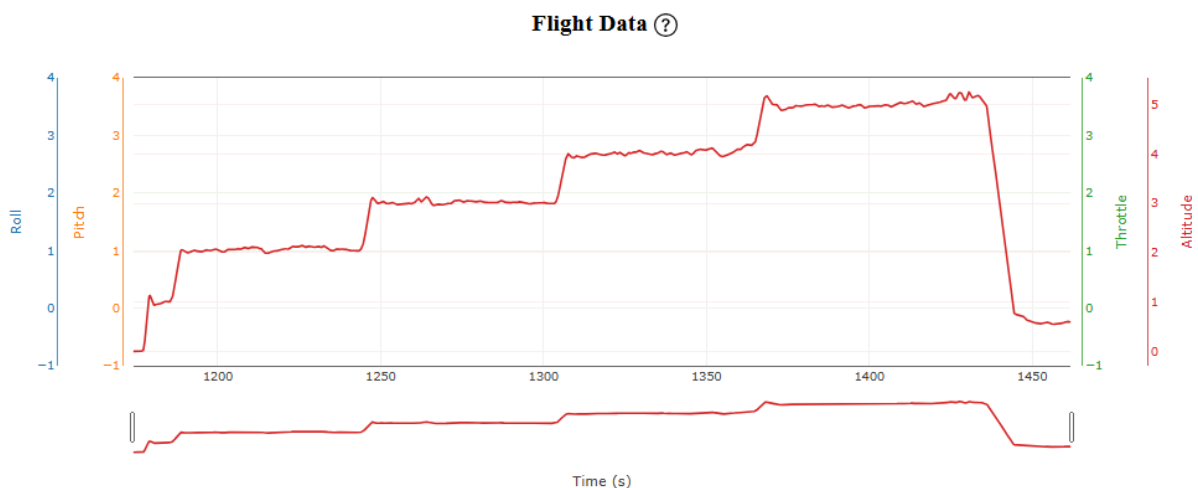


Figure 3-21: Notch filtering flight data

Several parameters need to be configured when applying a notch filter. The first one is `INS_HNTCH_ENABLE`. Placing this one to “enabled” will activate the Harmonic Notch (HNTCH) algorithm during flight. The second parameter `INS_HNTCH_MODE` is set to ESC telemetry, this indicates that the filter’s centre frequency is dynamically updated based on the real-time rotational speed data transmitted by the ESC’s. This offers significant advantages over static frequency configurations, as the dominant vibrations are directly proportional to the motors rotational speed. The `INS_HNTCH_FREQ`

specifies the fundamental rotational frequency of the motors. The value is set to 40Hz, which indicates that the primary vibration component is anticipated to occur around this frequency. The *INS_HNTCH_BW* is set to 20Hz and defines the bandwidth of the notch filter around its centre frequency. A value of 20 Hz indicates that the filter will significantly attenuate frequencies within a range of ± 10 Hz around each targeted harmonic. *INS_HNTCH_ATT* is set to 40 dB and sets the attenuation level of the notch filter in decibels (dB). A value of 40 dB signifies a substantial reduction in the amplitude of the signals within the filter's bandwidth. The *INS_HNTCH_HMCS* specifies the number of harmonic frequencies that the HNTCH will simultaneously filter. This is set to 3, which indicates that the fundamental frequency and its first two harmonic frequencies will be filtered. *INS_HNTCH_OPTS* is set to 1, this introduces a double notch instead of a single notch at each targeted harmonic frequency. A double notch filter provides potentially better attenuation than a single notch filter.

Figure 3-22 The plot illustrates the frequency response of a harmonic notch filter during flight. The X-axis represents the frequency in hertz [Hz], while the Y-axis corresponds to the amplitude of gyroscopic vibrations. Two prominent harmonic vibration peaks are observed at approximately 80 Hz and 160 Hz, corresponding to the first and second harmonic. These frequencies are effectively attenuated by the harmonic notch filter, as indicated by the vertical grey lines and the surrounding shaded grey regions, which denote the filter's active attenuation bands. The blue curve depicts the unfiltered (pre-filter) vibration amplitude of the first gyroscope during flight, showing significant energy at the harmonic frequencies. In contrast, the orange curve represents the post-filter gyroscope output, demonstrating substantial suppression of the vibration peaks at the targeted frequencies. The green curve projects the expected vibration profile for the first gyroscope in a future flight, assuming the current harmonic notch filter configuration remains unchanged. This visualization confirms the effectiveness of the harmonic notch filter in mitigating vibrational noise and improving sensor signal quality during flight.

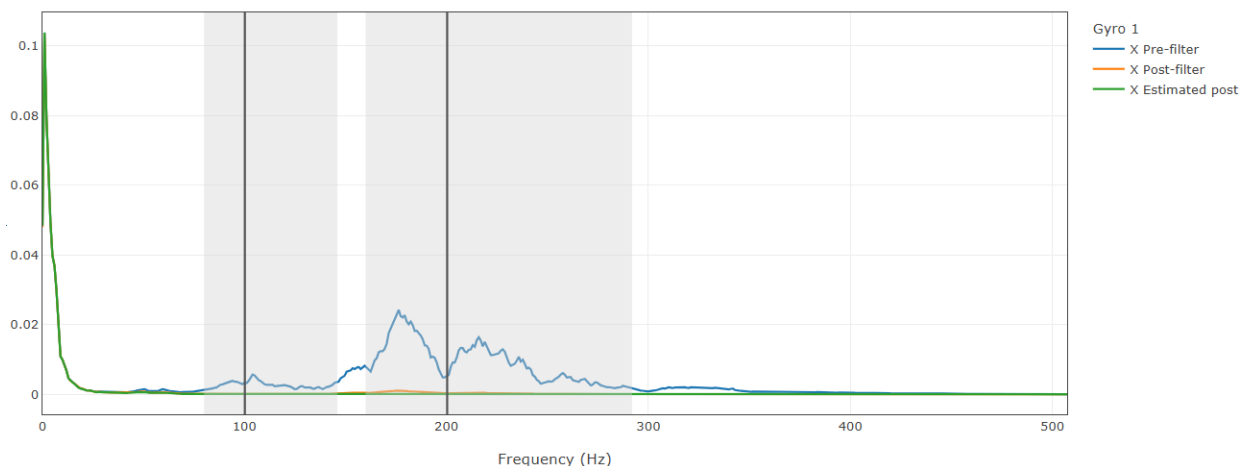


Figure 3-22: Harmonic notch filtering setup

3.5.5 PID VTOL QuickTune

The PID quicktune uses a lua script, which is a script that can be executed by your flight controller in flight. It simplifies the process of finding a good tune for a multicopter's attitude control parameters. During the script the P, I and D values for the Roll, Pitch and Yaw for the vehicle will be determined. The script slowly increases the relevant gains until it detects oscillation. It then reduces the gains by 60% and moves onto the next gain. Once all the gains have been tuned the tune completes and the user can decide to save or discard the new gains. The advantage of a QuickTune over an AutoTune is that it is much safer because the vehicle does not need to be manually moved during the flight. It will simply hover in loiter and execute the lua script. By executing this script *ATC_RAT_RLL_D*, *ATC_RAT_RLL_P*,

ATC_RAT_RLL_I (PID values for the roll movement), *ATC_RAT_PIT_D*, *ATC_RAT_PIT_P*, *ATC_RAT_PIT_I* (PID values for the pitch movement), *ATC_RAT_YAW_D*, *ATC_RAT_YAW_P* and *ATC_RAT_YAW_I* (PID values for the yaw movement) were defined.

3.5.6 MagFit calibration

The MagFit calibration tool is a tool that can be used to perform finetune your compass calibration. This will be done via an online tool that will calculate the “MAGFit inflight calibration”. Calibration parameters are found that fit the measured magnetic field from the log to the expected field from the World Magnetic Model. For best results use a flight log that covers as many orientations as possible. Different calibration compensation techniques can be used.

The first method utilizes no motor compensation. This method focuses on correcting inherent biases and distortions in the magnetometer itself, without explicitly accounting for the magnetic interference caused by the drone's motors. It aims to minimize the average error between the measured magnetic field in the flight log and the expected magnetic field from the WMM by applying various correction parameters. Here are the compensation techniques within this first method:

- *Compass Offset*: This is the most basic correction. A compass offset accounts for a constant, fixed magnetic field that is consistently biasing the magnetometer readings in a particular direction. The MagFit tool will calculate an (x, y, z) offset vector that, when subtracted from the raw magnetometer readings, shifts the data closer to the expected values.
- *Offset and Scale*: This technique goes a step further by not only correcting for a constant offset but also for scaling errors. Scaling errors occur when the magnetometer's sensitivity is not uniform across all axes. For instance, a 1 mGauss change in the actual magnetic field might be reported as a 0.9 mGauss change by the sensor along one axis and a 1.1 mGauss change along another. The MagFit tool will determine an offset vector (x, y, z) and a scaling matrix (often a diagonal matrix with scale factors for each axis) to correct these non-uniform sensitivities. This helps to ensure that the magnitude of the measured magnetic field aligns better with the expected magnitude.
- *Offset and Iron* (Soft Iron and Hard Iron Compensation): This correction method is the most complete within the "no motor compensation" category. It addresses both hard iron (permanent magnet) and soft iron distortions (temporarily magnetized by the Earth's magnetic field).

The second method utilizes motor compensation with extends the first method by explicitly modelling and compensation for the dynamic interference generated by the current flowing through the drone's power system. The MagFit tool will analyse the relationship between the logged battery current and the deviations in the magnetometer readings from the expected WMM values. It will attempt to model the magnetic field generated by the current flow.

[Figure 3-23](#) shows that the mean field error for compass 1 (compass with priority number 1) is approximately 70 mGauss and 75 mGauss for compass 2 (compass with priority number 2). After the calibration with offsets and no motor compensation this mean field error can be reduced to 18 mGauss for compass 1 and 20 mGauss for compass 2. It is also clear that scaling of battery compensation won't introduce an additional decrease in the mean field error. Therefore only the compass offsets will be calibrated out of the signal.

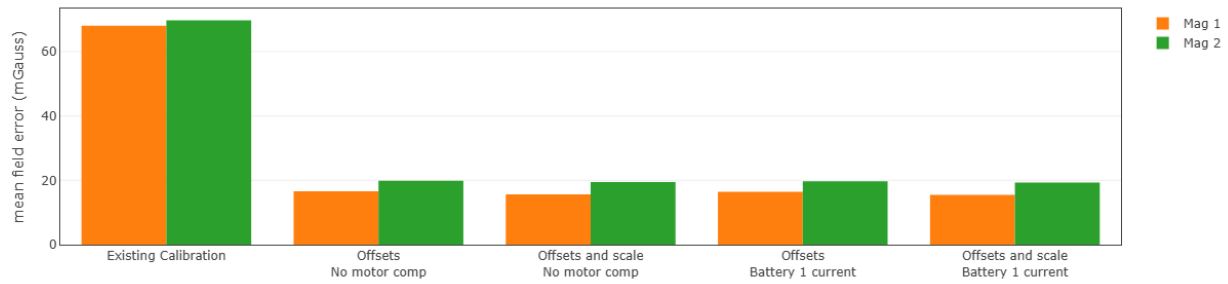


Figure 3-23 Mean field error in [mGauss]

Figure 3-24 shows the Y field strength in [mGauss] during a flight pre-calibration and post-calibration. The black graph shows the expected field from the WMM. The yellow and red graph show the current calibration for compass 1 and compass 2. The green and purple graphs show the calibration for compass 1 and compass 2 after correcting for the offsets (without motor compensation). After the correction they lie significantly closer to the WMM field.

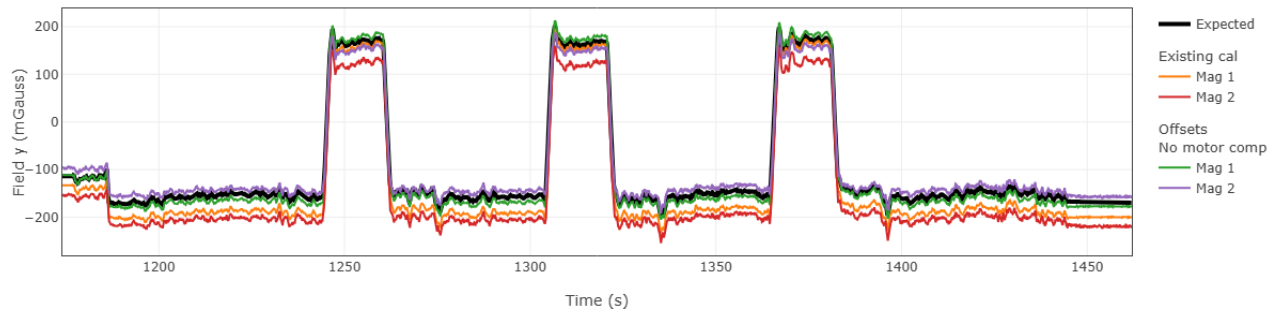


Figure 3-24: Magnetic Y field in [mGauss] before and after MAGfit calibration

3.6 The software architecture

The autonomous flight is achieved through a sophisticated software architecture. Communication between the Raspberry Pi 4B and the Pixhawk is established via a serial connection on `"/dev/serial0"`, which transmits MAVLink 2 commands from the Raspberry Pi 4B to the flightcontroller. These commands are generated using a Python script that leverages the pymavlink library. The autonomous flight sequence consists of several key phases: arming, takeoff in guided mode, flying waypoints in auto mode, and finally returning to launch (RTL) in auto mode. Initially, the drone is armed in stabilize mode, after which it transitions to guided mode for takeoff. Once airborne, it switches to auto mode, navigating through waypoints arranged in a vertical grid. While the drone follows the waypoints, a separate thread on `"/dev/ttyUSB0"` is initiated to handle 5G measurements, with data collection occurring during a loiter phase at each waypoint. Waypoint creation is managed by an independent Python script, which stores these waypoints in a .txt file. At all times, the RC controller remains active, allowing manual takeover if the script fails to execute as expected.

3.6.1 Autonomous flight

Code [Snippet 1](#) shows the first part of the autonomous flight script in Python. First three important global variables are defined:

- `Current_waypoint`: This integer will keep track of the waypoint where the drone is currently hovering.

- *Max_waypoints*: This integer defines the maximum amount of waypoints that will be flown in the autonomous mission.
- *Logging*: This boolean tracks if the drone is currently logging measurements in a waypoint or not.

Then the serial communication between the Raspberry Pi 4B and the triaxial 5G sensor is established. In this serial communication a comma separated values (csv) file is created with a filename that can be modified and the columns for the first row are configured as “Timestamp”, “Current_waypoint”, “Min_X”, “Max_X”, “Avg_X”, “Med_X”, “Min_Y”, “Max_Y”, “Avg_Y”, “Med_Y”, “Min_Z”, “Max_Z”, “Avg_Z” and “Med_Z”.

```
from pymavlink import mavutil
import time
import serial
import csv
import os
import threading

##PARAMETERS for serial data connection##
# Global variable to control whether to log or not
current_waypoint = 1
max_waypoints = 16
logging = False

# Setup the serial connection to the 5G sensor
serial_port = '/dev/USB0' # Adress from the 5G sensor
baud_rate = 115200 # Baud rate communication
ser = serial.Serial(serial_port, baud_rate, timeout=1)

csv_dir = "/Metingen"
os.makedirs(csv_dir, exist_ok=True)
timestamp = time.strftime("%Y-%m-%d_%H-%M-%S")
csv_filename = os.path.join(csv_dir, "test_23_04_25.csv")

if not os.path.exists(csv_filename):
    with open(csv_filename, mode='w', newline='') as file:
        writer = csv.writer(file)
        writer.writerow(["Timestamp", "Current_Waypoint", "Min_X",
                        "Max_X", "Avg_X", "Med_X",
                        "Min_Y", "Max_Y", "Avg_Y", "Med_Y",
                        "Min_Z", "Max_Z", "Avg_Z", "Med_Z"])
```

Snippet 1: Autonomous flight part 1

[Snippet 2](#) shows the connection initialization and the first two functions. On line 37 a persistent bidirectional link between the ground control script and the autopilot system is created by opening a connection on `/dev/ttyAMA0`. This is the UART port on a Raspberry Pi. The `mavutil.mavlink_connection()` function is part of the Pymavlink library and abstracts the lower-level serial I/O, framing, and synchronization necessary for sending and receiving MAVLink messages in real time. On line 41 there is waited on a MAVlink heartbeat, which is a periodically broadcasted telemetry signal (typically 1 Hz) that communicates the drone system's presence and availability. This mechanism is fundamental to synchronization and handshake protocols in distributed real-time systems.

The `set_mode(mode)` function sends a MAVLink command to the drone to change its current flight mode to a specified mode, such as "GUIDED", "LOITER", "AUTO", etc. Line 47 retrieves the numerical mode ID corresponding to the desired flight mode (passed as a string) from the drone's available mode mapping dictionary. In this function the `master.mav.set_mode_send` initiates a MAVLink message of the type `SET_MODE`, it requires three variables: `master.target_system` (the target system to which the mode change command is directed), `mavutil.mavlink.MAV_MODE_FLAG_CUSTOM_MODE_ENABLED` (this indicates the type of mode switching) and the `mode_id` (provides the numerical mode ID retrieved earlier, which defines the new operational state of the drone).

The `send_mavlink_command` function constructs and transmits a MAVLink `COMMAND_LONG` message to a target drone. This message type is used for executing a wide variety of high-level commands: from arming/disarming the vehicle to initiating mission actions or controlling onboard peripherals. The `master.mav.command_long_send` method initiates a message from the type `COMMAND_LONG_SEND` and requires 11 parameters. The `master.target_system` and `master.target_component` specify the destination identifiers for the MAVlink message. The system is the drone and the component is the autopilot. The command specifies the MAVlink command ID that needs to be executed. The 0 is a confirmation flag. Then 7 different parameters are sent. Depending on the selected command, these values can represent anything from altitude, heading, and velocity to camera shutter time or servo position. The `COMMAND_LONG` message format standardizes how diverse instructions are encoded and communicated over MAVLink.

```

##PARAMETERS for the drone connectivity##
#connect with the drone
master = mavutil.mavlink_connection("/dev/ttyAMA0")

# Wait for the heartbeat msg to find the system ID
master.wait_heartbeat()
print("Heartbeat received, the system is ready to start the flight.")

# Set a desired flight mode
def set_mode(mode):
    mode_id = master.mode_mapping()[mode] # dict with keys -> code names
    #and the values are the mode IDs (integers)
    master.mav.set_mode_send(
        master.target_system, # The target system is the drone itself
        mavutil.mavlink.MAV_MODE_FLAG_CUSTOM_MODE_ENABLED,
        mode_id) # The mode string that we want to set
    print(f"Setting mode to {mode}...")

# Function to send commands by MAVlinks 7 parameters for the drone
# This function can be used for sending all commands that require 7 parameters
def send_mavlink_command(master, command, param1=0, param2=0, param3=0, param4=0, param5=0,
param6=0, param7=0):
    master.mav.command_long_send(
        master.target_system, master.target_component, # Drone itself
        command, # The command that needed to be send
        0, # 0 equals no confirmation required
        param1, param2, param3, param4, param5, param6, param7
    )

```

Snippet 2: Autonomous drone flight part 2

[Snippet 3](#) shows the function `def arm()`, `def disarm()` and `def takeoff(altitude)`. In these three functions the function `send_mavlink_command`, which was defined earlier is used.

In `def arm()` the drone is armed. It sends a `COMMAND_LONG` message with command ID `MAV_CMD_COMPONENT_ARM_DISARM` and parameter 1 set to 1 (true). Arming is a critical safety mechanism in unmanned aerial systems (UAS). The arming command transitions the drone's motor controllers from an idle state to an active state, enabling thrust generation. This is often blocked if safety conditions (e.g., GPS lock, valid orientation) are not met. Then there will be continuously listened for MAVLink heartbeat messages, blocking further execution until a valid one is received. Once the `MAV_MODE_FLAG_SAFETY_ARMED` flag is detected in `base_mode`, arming is confirmed.

The `def disarm()` function mirrors the `def arm()` function, with the only difference is that the `COMMAND_LONG`'s parameter is now set 0 (false) instead of 1. It also ensures the absence of the `MAV_MODE_FLAG_SAFETY_ARMED` flag.

The `def takeoff(altitude)` function issues a takeoff, instructing the autopilot to autonomously ascend to a given altitude with the MAVLink navigation command `MAV_CMD_NAV_TAKEOFF`. In parameter 7 the target relative altitude (in meters) is defined. This is interpreted relative to the current home location.

```
#The function to arm the drone
def arm():
    send_mavlink_command(master,mavutil.mavlink.MAV_CMD_COMPONENT_ARM_DISARM,1)
    # param 1 = 1 to arm, 0 to disarm, param 2 is used or forced arming/disarming (not used here)
    print("Arming the drone...")
    while True: #This will block further execution until the drone is armed
        master.recv_match(type='HEARTBEAT', blocking=True)
# Wait for heartbeat with base_mode
    #(operating mode: armed, disarmed, manual,...),
#custom_mode (specific flight mode: GUIDED, AUTO) and system_status(booting, standby, active)
    if master.field('HEARTBEAT', 'base_mode') &
        #Base_mode contains bit flags the indicate the systems state and
        MAV_MODE_FLAG_SAFETY_ARMED
        #is a flag that indicates that the drone is armed
        print("The drone was succesfully armed!")
        break

# The function to disarm the drone
def disarm(): # The function to disarm the drone
    send_mavlink_command(master, mavutil.mavlink.MAV_CMD_COMPONENT_ARM_DISARM, 0)
    # param 1 = 0 to disarm
    print("Disarming the drone...")
    while True: # This will block further execution until the drone is disarmed
        master.recv_match(type='HEARTBEAT', blocking=True) # Wait for updated heartbeat message
        if not (master.field('HEARTBEAT', 'base_mode') &
            mavutil.mavlink.MAV_MODE_FLAG_SAFETY_ARMED):
            # Check if the armed flag is no longer set in base_mode
            print("Drone was succesfully disarmed!")
            break

# The function to take off the drone
def takeoff(altitude):
    send_mavlink_command(master, mavutil.mavlink.MAV_CMD_NAV_TAKEOFF, param7=altitude)
    print(f"Taking off to {altitude} meters...")
```

Snippet 3: Autonomous drone flight part 3

[Snippet 4](#) shows the `def log_data_n_times(n=10)` function. This function will be executed in a logging thread and will store 5G measurements on the memory of the Raspberry Pi 4B. The logging boolean becomes true and 10 measurements are taken in each waypoint (equals to 10 seconds of hovering because the sensor publishes one measurement in its `sendTask` every second). As long as the measurement count is less than 10, the RF-EMF exposure data as well as the current timestamp and

the current waypoint is written on a new row of the csv file. This thread will be executed every time an enter is pressed, while the drone is flying its waypoints.

```
def log_data_n_times(n=10):
    global logging, current_waypoint

    logging = True
    count = 0
    print(f"[Waypoint {current_waypoint}] Logging {n} data samples...")

    while count < n:
        try:
            data = ser.readline().decode('utf-8').strip()
            if data:
                print(f"Serial Data: {data}")
                if data.startswith("DATA"):
                    parts = data.split(",")
                    timestamp = time.strftime("%Y-%m-%d %H:%M:%S")
                    min_x, max_x, avg_x, med_x = map(float, parts[2:6])
                    min_y, max_y, avg_y, med_y = map(float, parts[6:10])
                    min_z, max_z, avg_z, med_z = map(float, parts[10:14])

                    with open(csv_filename, mode='a', newline='') as file:
                        writer = csv.writer(file)
                        writer.writerow([timestamp, current_waypoint, min_x, max_x, avg_x, med_x,
                                        min_y, max_y, avg_y, med_y,
                                        min_z, max_z, avg_z, med_z])

                    count += 1

        except Exception as e:
            print(f"Error reading from serial port: {e}")
    print(f"Done logging for waypoint {current_waypoint}")
    logging = False
    current_waypoint += 1
```

Snippet 4: Autonomous drone flight part 4

[Snippet 5](#) shows the sequence in which the functions are called. First the mode is changed to STABILIZE. This the only mode that the drone can be armed in. Then the drone is armed. After that is put into GUIDED mode. This done because the drone cannot takeoff in STABILIZE mode on the autopilot, but it can in GUIDED mode. It then takes off to approximately 2 meters. The drone is given 10 seconds to ascend to 2 meters and hovers for the remaining seconds at that altitude. Then the drone is put into AUTO mode. In this mode the .txt file containing all the waypoint location will be executed. The start_mission_logging() function is also started. This will start a 10-second logging thread every time an enter in the terminal is pressed.

```
# Call the function
set_mode("STABILIZE")
arm()
set_mode("GUIDED")
takeoff(2)
time.sleep(10)
set_mode("AUTO")
start_mission_logging()
```

Snippet 5: Autonomous drone flight part 5

3.6.2 Waypoint editor

Once the flight mode is changed to AUTO it will start to fly the waypoints. These waypoints can be preconfigured in the Missionplanner software. [Figure 3-25](#) shows the predefined flight path. 16 waypoints in total are defined. Every 4 waypoints the altitude is incremented by 1m. The first 4 waypoints start at an altitude of 2m and the last 4 end at an altitude of 5m. Each waypoint lies 1.5m out of each other. This creates a vertical grid of $4.5 \text{ m} \times 3 \text{ m} = 13.5 \text{ m}^2$. In each waypoint a delay of 10 seconds is introduced. This results in the drone hovering for 10 seconds in each waypoint. During these 10 seconds the RF-EMF exposure measurements will be taken. These measurements will then be analysed in the field in a separate python file. This will calculate the total received power in each waypoint and give a general idea of the exposure that has been measured. Later these measurements will be further analysed to create the final vertical exposure grid by applying Kriging.

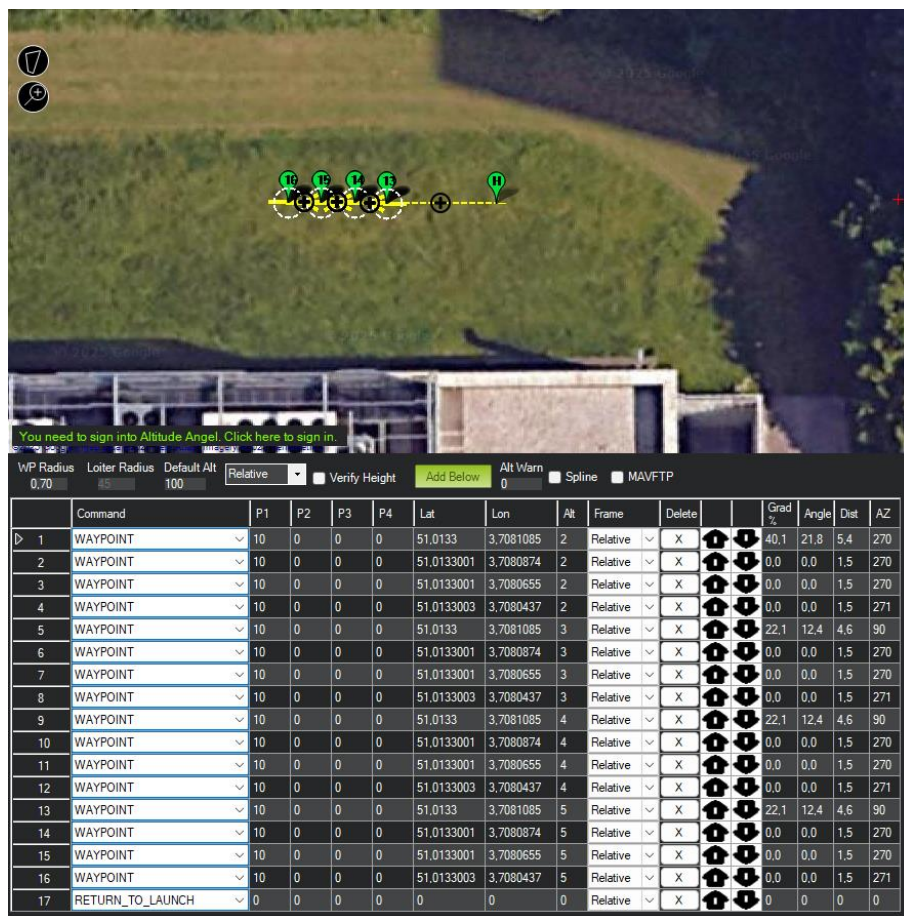


Figure 3-25: Waypoint editor in Mission planner for the vertical grid

4. Results

4.1 Onboard electronics influence experiments

4.1.1 Measurement setups

As discussed in [Section 3.4.2](#) two measurement campaigns are conducted. [Figure 4-1](#) shows the 5G sensor's orientation during them: pointing up in the first one and pointing down in the second. The central part of the mounting is now rotated over 180° and is again attached with eight screws to the landing poles of the drone. Both measurement campaigns will conduct similar experiments, allowing for a comparison that helps define the sensor orientation (upward or downward), which minimizes influence by the onboard electronics.



Figure 4-1: Measurement setup campaign 1: 5G sensor pointing up (a) Measurement setup campaign 2: 5G sensor pointing down (b)

Initially the RC IA6B receiver's antennas were mounted freely on the carbon-fiber top plate of the drone and could be oriented freely. Preliminary tests revealed that the orientation of the receiver antennas significantly influenced the received power P_r on the 5G sensor. To systematically evaluate this effect, three antenna orientation scenarios were defined, as illustrated in [Figure 4-2](#). When the receiver antennas are oriented downward at -90° , they are positioned through designated openings in both the carbon-fiber top and bottom plates. At 0° , the receiver is affixed horizontally on the carbon-fiber top plate. For the 90° configuration, the antennas are directed vertically upward and secured adjacent to the flight controller in the middle of the carbon-fiber top plate and attached to its left side with tape.

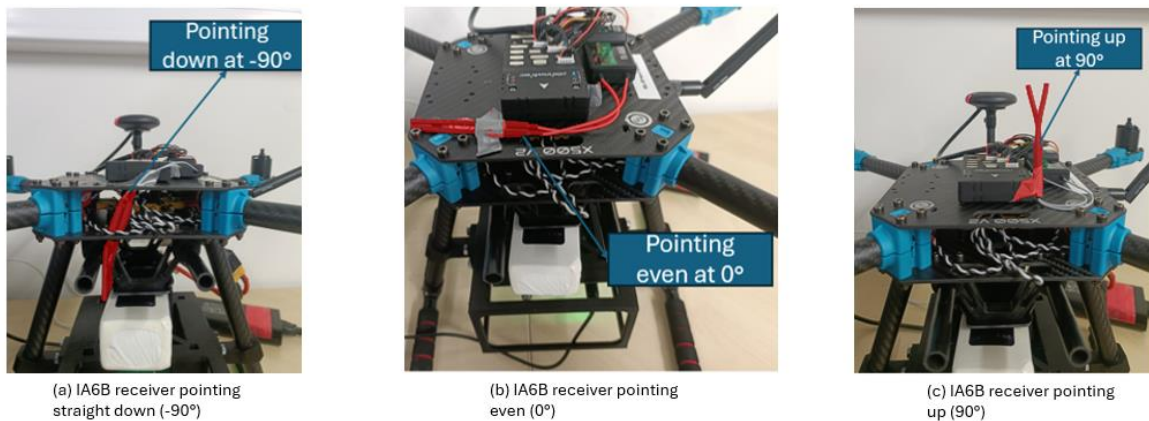


Figure 4-2: The RC IA6B receiver's antennas pointing down at -90° (a), pointing even at 0° (b) and pointing up at 90° (c)

[Figure 4-3](#) illustrates the telemetry and RC communication links used in the experimental setup. In several experiments, a telemetry connection is established between the GCS and the drone's flight

controller, operating at 433 MHz. This link continuously transmits flight status data (e.g., altitude, heading, battery voltage, and other telemetry parameters) from the flight controller to the GCS, thereby maintaining a constant data transmission stream during flight. Simultaneously, the RC link is maintained between the Flysky FS-i6X transmitter and the IA6B receiver onboard the drone. This RC connection operates in the 2.4 GHz band and remains active throughout the experiment, enabling real-time transmission of control inputs such as throttle, yaw, roll, and pitch. The persistent activity of both the telemetry and RC links introduces potential sources of electromagnetic emissions, which are relevant for evaluating their influence on the 5G sensor's received power measurements.

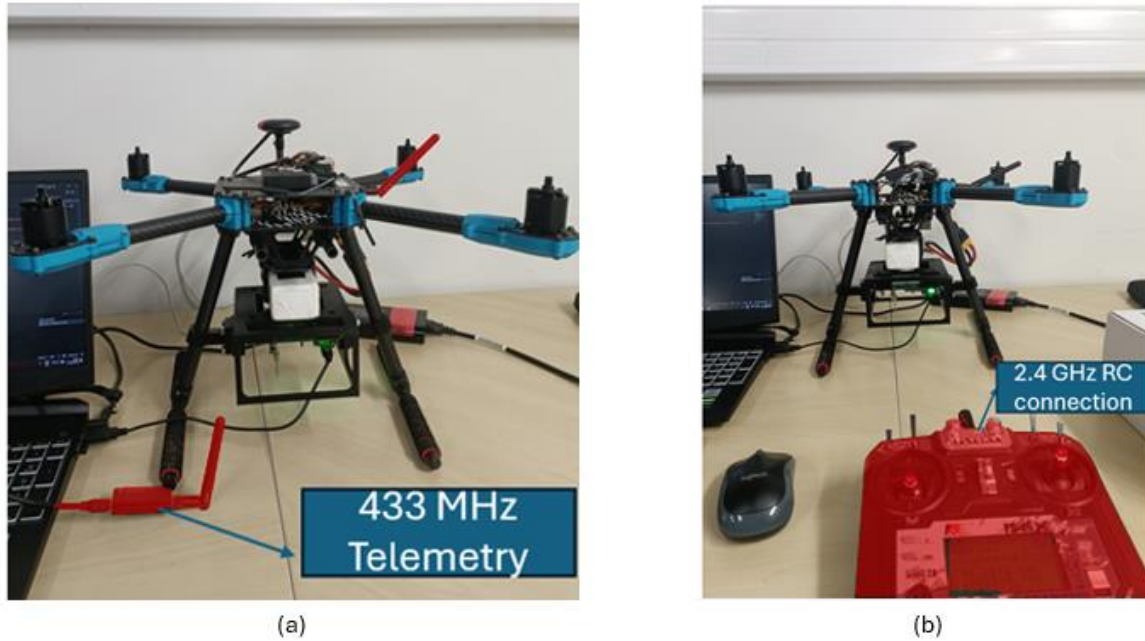


Figure 4-3: Telemetry connection between GCS and drone at 433 MHz (a) 2.4 GHz RC connection between fs i6X controller and IA6B receiver at 2.4 GHz

4.1.2 First measurement campaign – 5G sensor pointing up

[Figure 4-1a](#) shows how the 5G triaxial sensor is mounted pointing up towards the lipo battery. Hence the influence of the drone's onboard electronics can be researched. The first measurement campaign consisted of 20 experiments, summarised in [Table 4-1](#). A concise overview of the experimental setup, the potential exposure frequencies detectable by the 5G sensor, and the measured power levels along each sensor axis during the experiment are summarized in the table below.

Table 4-1: Drone influence experiments of the first campaign

Experiment #	Description	Exposure Frequencies	P_r [dBm]
1	The drone and its onboard-electronics remain unpowered.	None	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.73$
2	The drone's onboard electronics are powered, but no RC or telemetry connection is active.	None	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.73$
3	The drone is powered, the BLDC motors run at 8000 RPM.	ESC switching frequency: 30kHz	$P_x = -55.72$ $P_y = -57.73$

			$P_z = -62.73$
4	A telemetry connection at 433MHz is established.	Telemetry: 433 MHz	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.26$
5	The telemetry connection at 433 MHz is active, the BLDC motors rotate at 8000 RPM.	ESC switching frequency: 30kHz, Telemetry: 433 MHz	$P_x = -55.73$, $P_y = -57.73$ $P_z = -62.56$
6	The telemetry connection at 433 MHz is active, the BLDC motors accelerate between 1800 and 4000 RPM.	Telemetry: 433 MHz, ESC switching frequency: 30kHz	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.73$
7, 11, 12	An RC connection at 2.4 GHz is established, with the receiver antenna positioned at -90° pointing straight down.	RC connection: 2.4GHz	7) $P_x = -54.96$ $P_y = -49.23$ $P_z = -47.95$ 11) $P_x = -52.17$ $P_y = -56.36$ $P_z = -53.21$ 12) $P_x = -52.23$ $P_y = -56.36$ $P_z = -53.18$
8, 13, 14	An RC connection at 2.4 GHz is active, with the receiver antenna positioned at 0° pointing even.	RC connection: 2.4GHz	8) $P_x = -55.71$ $P_y = -54.91$ $P_z = -57.26$ 13) $P_x = -55.27$ $P_y = -57.05$ $P_z = -56.97$ 14) $P_x = -55.28$ $P_y = -57.07$ $P_z = -57.10$
9, 15,16	An RC connection at 2.4 GHz is active, with the receiver antenna positioned at 90° pointing straight up.	RC connection: 2.4GHz	9) $P_x = -55.48$ $P_y = -57.60$ $P_z = -55.61$ 15) $P_x = -55.70$ $P_y = -57.30$ $P_z = -58.93$ 16) $P_x = -55.73$ $P_y = -57.40$ $P_z = -59.18$
10	An RC connection at 2.4 GHz is active, with the receiver antenna at 90°, the BLDC motors rotate at 8000 RPM	RC connection: 2.4GHz; ESC switching frequency: 30kHz	$P_x = -55.73$ $P_y = -54.50$ $P_z = -52.40$

17	The drone's startup sequence is monitored while the RC system is powered on.	RC connection: 2.4GHz	$P_x = -54.83$ $P_y = -57.16$ $P_z = -55.70$
18, 19, 20	Simulating real influence during a flight: an RC connection at 2.4 GHz and a telemetry connection at 433 MHz are active.	RC connection: 2.4GHz, Telemetry connection: 433MHz	18) $P_x = -55.73$ $P_y = -57.71$ $P_z = -55.51$ 19) $P_x = -55.73$ $P_y = -57.73$ $P_z = -55.08$ 20) $P_x = -55.57$ $P_y = -57.72$ $P_z = -55.32$

Figure 4-4 shows an overview of the received power P_r in [dBm] during the experiments from the first measurement campaign.

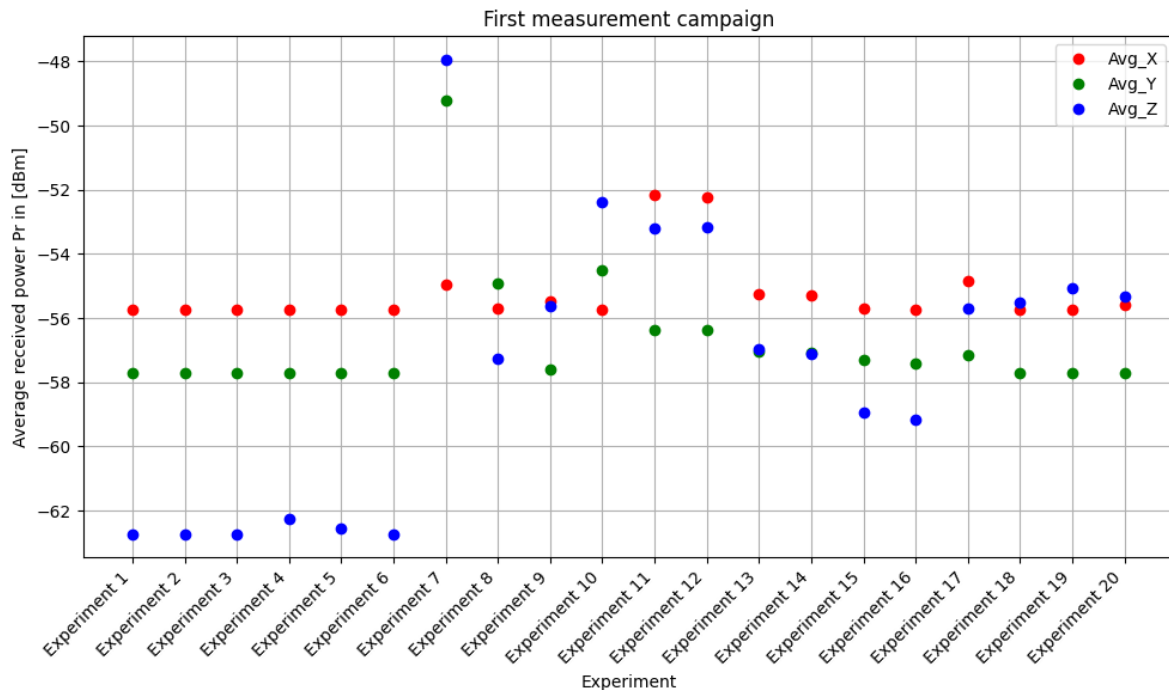


Figure 4-4: Average received power P_r in [dBm] during the 20 experiments from the first measurement campaign

Experiment 1 demonstrated that the 5G sensor did not register any environmental noise above its baseline. Although Wi-Fi networks such as iVisitor and eduroam were present within the iGent building where the experiments took place, the measured power remained at the noise floor across all three axes. This confirms that interference from ambient wireless signals is negligible, thereby validating the suitability of the laboratory environment for subsequent experiments.

Powering the onboard electronics in experiment 2 did not result in any measurable interference, which shows that the current drawn by them isn't detectable by the 5G sensor. In experiment 3, the BLDC motors were operated at 8000 RPM by controlling their PWM servo value directly via a MAVlink 2 command from the Raspberry Pi. This rotational speed represents a practical upper limit, as a higher rotational speed of the BLDC motors is not expected during actual flight. The received power levels

across all three axes remained at the noise floor, indicating that neither mechanical vibrations nor electromagnetic fields induced by the current drawn from the BLDC motors introduced measurable interference. This result supports the 5G sensor's robustness against onboard vibrational and EMI-related disturbances.

In experiments 4 through 6, a telemetry connection operating at 433 MHz was established. To ensure active data transmission (including parameters such as drone position, altitude, and heading) the Mission Planner software was launched, enabling a wireless link between the GCS and the flight controller via the 433 MHz channel. During experiment 4, the Z-axis antenna recorded a received power of $P_z = -62.26$ dBm, and in experiment 5, $P_z = -62.56$ dBm, both slightly above the sensor's noise floor of -62.73 dBm. However, in experiment 6, where the telemetry link remained active and the motors were operated between 1800 and 4000 RPM, the measured Z-axis power returned to the noise floor. These results suggest that the marginal increase observed in experiments 4 and 5 may be attributable to environmental noise rather than interference from the telemetry system itself. This hypothesis will be further investigated in the second measurement campaign.

During experiments 7 until 16 an RC connection at 2.4GHz was established. [Figure 4-2](#) shows the different orientations of the receiver's antennas. In experiments 7, 11 and 12, the receiver antennas were oriented vertically downward at -90° . In experiments 8, 13 and 14, the antennas were positioned horizontally at 0° . In experiments 9, 15 and 16, the antennas were directed vertically upward at 90° . [Table 4-2](#) summarizes the results from these experiments

Table 4-2: Received power P_r during experiments 10 through 16

Experiments 10 → 16	P_x [dBm]		P_y [dBm]		P_z [dBm]	
-90°	-52.17	-52.23	-56.36	-56.36	-53.21	-53.18
0°	-55.27	-55.28	-57.05	-57.05	-56.97	-57.05
90°	-55.70	-55.73	-57.30	-57.40	-58.93	-59.18

Orienting the receiver's antennas vertically upward (90°) resulted in the lowest levels of received power, indicating reduced interference. This configuration is therefore the most favourable for conducting measurements, as it effectively lowers the noise floor and enhances the sensor's ability to detect weak signals.

experiments 18, 19 and 20 simulated a realistic drone flight scenario by introducing a 2.4 GHz RC link (with antennas oriented upward at 90°) and a 433 MHz telemetry connection between the GCS and the drone. The received power P_x varied by 0.16 dBm between experiments 18 and 20, P_y showed a variation of 0.02 dBm between experiments 18 and 19, and P_z exhibited the largest variation of 0.43 dBm between experiments 18 and 19. The total received power across the X, Y, and Z axes was calculated using the root sum of squares method, serving as an estimate of the drone's electromagnetic noise level during flight. This baseline noise level was determined to be -53.50 dBm, indicating that any signal exceeding this threshold should be detectable during actual drone operation.

4.1.3 Second measurement campaign – 5G sensor pointing down

[Figure 4-1b](#) illustrates the experimental setup used during the second measurement campaign. [Table 4-3](#) shows 16 experiments with similar structure as in [Section 4.1.2](#).

Table 4-3: Drone influence experiments during the second measurement campaign

Experiment #	Description	Exposure Frequencies	P_r [dBm]
1	The drone and its onboard-electronics remain unpowered.	None	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.73$
2	The drone's onboard electronics are powered, but no RC or telemetry connection is active.	None	$P_x = -55.73$ $P_y = -57.73$ $P_z = -60.73$
3	A telemetry connection at 433 MHz is established.	Telemetry: 433 MHz	$P_x = -55.73$ $P_y = -57.73$ $P_z = -60.73$
4	A telemetry connection at 433 MHz is established.	Telemetry: 433 MHz	$P_x = -55.73$, $P_y = -57.73$ $P_z = -60.73$
5	The signal generator sends a 433 MHz signal with an attenuation of 18 dBm in the lab.	Telemetry: 433 MHz,	$P_x = -55.73$ $P_y = -57.73$ $P_z = -62.73$
6, 7, 8	An RC connection at 2.4 GHz is established with the receiver antenna positioned at -90° pointing straight down.	RC connection: 2.4GHz	6) $P_x = -52.88$ $P_y = -55.08$ $P_z = -48.86$ 7) $P_x = -52.72$ $P_y = -55.07$ $P_z = -48.27$ 8) $P_x = -52.98$ $P_y = -55.03$ $P_z = -48.27$
9, 10, 11	An RC connection at 2.4 GHz is established with the receiver antenna positioned at 0° pointing even.	RC connection: 2.4GHz;	9) $P_x = -53.90$ $P_y = -55.01$ $P_z = -51.38$ 10) $P_x = -53.59$ $P_y = -55.01$ $P_z = -51.42$ 11) $P_x = -53.88$ $P_y = -55.18$ $P_z = -51.65$
12, 13, 14	An RC connection at 2.4 GHz is established with the receiver antenna positioned at 90° pointing straight up.	RC connection: 2.4GHz	12) $P_x = -55.14$ $P_y = -57.68$ $P_z = -51.33$ 13) $P_x = -55.31$ $P_y = -57.72$ $P_z = -51.07$

			14) $P_x = -55.33$ $P_y = -57.73$ $P_z = -51.45$
15, 16	Simulating real influence during a flight: an RC connection at 2.4 GHz and a telemetry connection at 433 MHz are active.	RC connection: 2.4GHz Telemetry: 433 MHz	15) $P_x = -54.24$ $P_y = -57.73$ $P_z = -50.47$ 16) $P_x = -54.41$ $P_y = -57.38$ $P_z = -50.64$

Figure 4-5 shows an overview of the received power P_r in [dBm] during the experiments from the second measurement campaign.

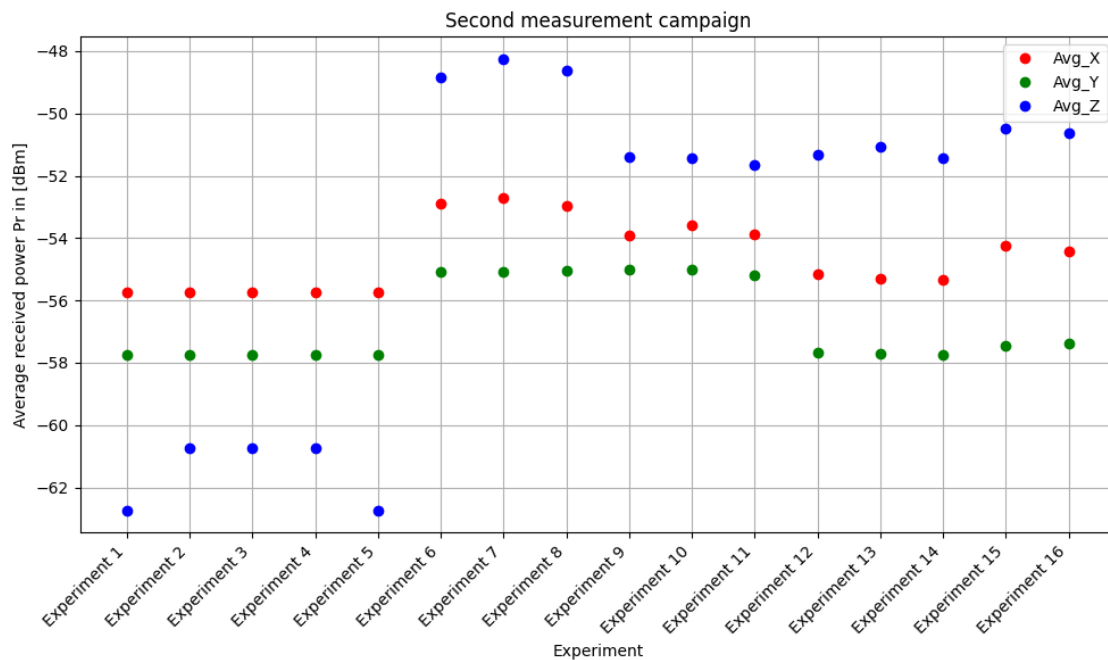


Figure 4-5: Average received power P_r in [dBm] during the 20 experiments from the second measurement campaign

Similar as in the first measurement campaign the transition from the drone's onboard electronics being powered off (experiment 1) towards the drone's onboard electronics getting powered on (experiment 2) had no effect on the sensor readings, which remained at the noise level for each axis.

During experiments 3 and 4 further research was conducted into the 433 MHz telemetry connection, as a slight increase in the detected power on the z-axis P_z had been observed in the first measurement campaign during experiments 4 and 5. However, during experiments 3 and 4, all received power levels remained at the noise floor of $P_x = -55.73$ dBm, $P_y = -57.73$ dBm and $P_z = -60.73$ dBm. To validate the previous findings, Experiment 5 was conducted using a waveform generator connected to a TX antenna positioned 2 meters from the triaxial 5G sensor, transmitting at an attenuation level of 18 dBm. Once again, all measured received power levels P_r remained at the sensor's noise floor. This confirms that the 433 MHz telemetry signal is not detectable by the triaxial 5G sensor, which aligns with expectations, as 433 MHz falls well outside the sensor's designated frequency sensitivity range.

During experiments 6 until 14 an RC connection at 2.4GHz was established. [Figure 4-2](#) shows the different orientations of the receiver's antennas. In experiments 6, 7 and 8, the receiver antennas were oriented vertically downward at -90° . In experiments 9, 10 and 11, the antennas were positioned horizontally at 0° . In experiments 12, 13 and 14, the antennas were directed vertically upward at 90° . [Table 4-4](#) summarizes the results from these experiments, the upward antenna orientation (90°) resulted in the least influence on the sensor's readings and is therefore identified as the most favourable configuration, consistent with the optimal orientation observed during the first measurement campaign.

Table 4-4: Received power P_r during experiments 6 through 14

Experiments 10 → 16	P_x [dBm]			P_y [dBm]			P_z [dBm]		
-90°	-52.88	-52.72	-52.98	-55.08	-55.07	-55.03	-48.86	-48.27	-48.27
0°	-53.90	-53.59	-53.88	-55.01	-55.01	-55.18	-51.38	-51.42	-51.65
90°	-55.14	-55.31	-55.33	-57.68	-57.72	-57.73	-51.33	-51.07	-51.45

In Experiments 15 and 16, both the 2.4 GHz RC link and the 433 MHz telemetry connection were active, while the BLDC motors were operated at 8000 RPM, thereby simulating realistic in-flight conditions. The received power levels P_r recorded in these experiments will be compared in [Section 4.1.4](#) with those obtained in Experiments 18, 19, and 20 from the first measurement campaign, to determine the most favourable orientation of the triaxial 5G sensor within its mount.

4.1.4 Comparison first and second measurement campaign

[Figure 4-6](#) shows the comparison between experiments 18, 19 and 20 from the first measurement campaign and 15 and 16 from the second measurement campaign. These experiments replicate the RF-EMF exposure generated by all onboard electronics during an actual drone flight. During these measurements, the 2.4 GHz link with the remote controller, the 433 MHz telemetry connection are active and the BLDC motors rotate at 8000 RPM. The total received power $P_{r,tot}$ is determined by computing the root sum of squares (RSS) of the received power measured along each individual axis.

$$P_{r,tot} = \sqrt{\sum_i P_{r,i}^2} \quad (4.1)$$

Where:

- $P_{r,tot}$ is the total measured power by the triaxial 5G sensor [W]
- $P_{r,i}$ is the measured power for an individual axis [W]
- i varies between the X-axis, Y-axis and Z-axis

It was observed that when the triaxial 5G sensor is oriented upside down, the measured exposure increases by approximately 3 dB compared to the upright configuration, corresponding to a twofold increase in received power. This indicates that orienting the sensor face-up effectively reduces potential interference by 50%. Consequently, the upright orientation has been selected for all subsequent measurements to ensure minimal perturbation of the sensor readings. The lipo battery induces a shielding effect against the interference from all onboard electronics, which could explain this reduction in received power, hence the upright position is beneficial.

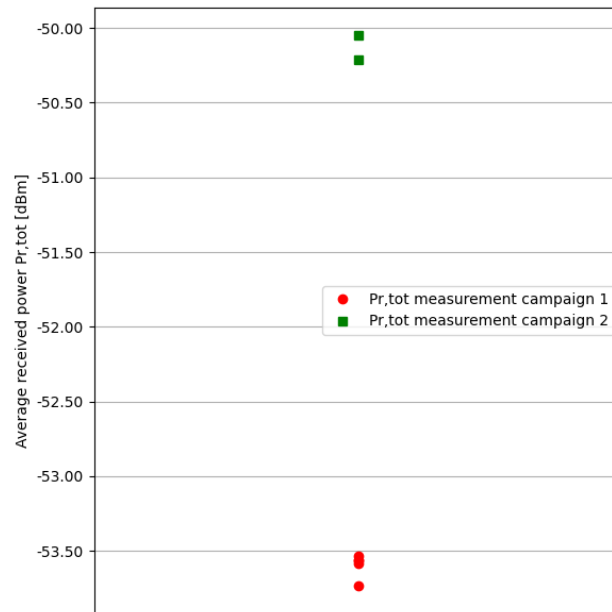


Figure 4-6: First and second measurement campaign comparison

Figure 4-7 illustrates the methodology used to determine the average received power P_r during the realistic flight scenario with the sensor in the upright orientation. The first three measurements were conducted on the same day, while the final two were performed on a different day to evaluate the reproducibility of the results. In these last two experiments, the RC controller and telemetry radio were positioned approximately 20 meters from the drone to assess whether an increased distance between them would influence the recorded exposure levels. The data indicate that the distance between the RC controller or the telemetry radio and the drone has no significant effect on the received total power $P_{r,tot}$. To establish the system's noise floor $P_{r,noise}$, defined as the total average received power below which exposure measurements are no longer considered reliable due to potential interference from onboard electronics, the mean total received power across all five realistic flight experiments was calculated. This yielded a noise floor -53.59 dBm.

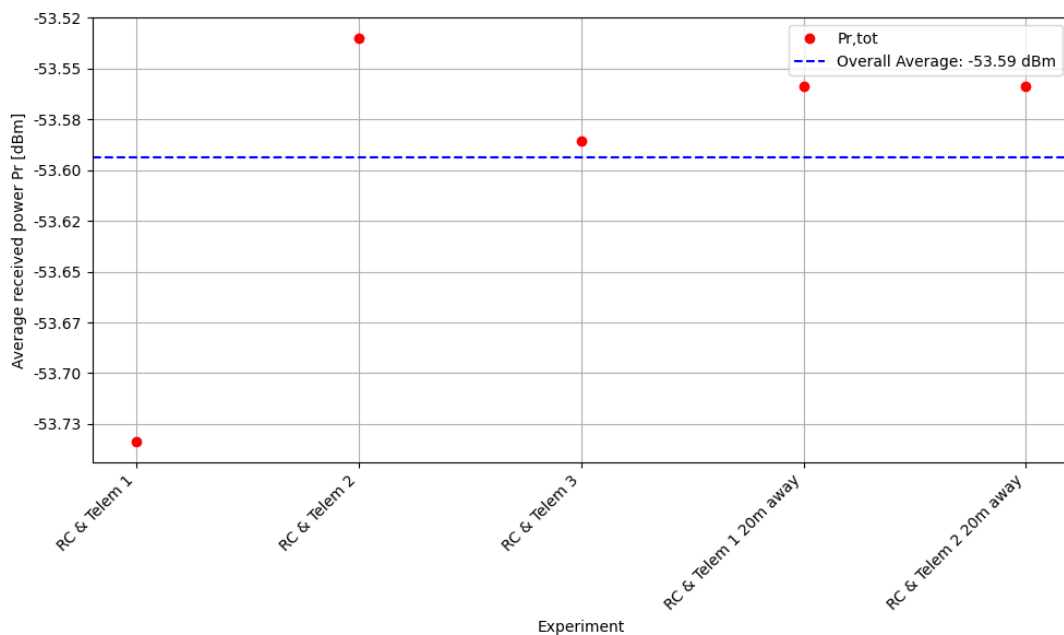


Figure 4-7: Quantified noise level of onboard electronics interference

4.2 The drone's shielding effect

The physical design of the drone, particularly the materials and arrangement of the components, can potentially create a shielding effect for a 5G sensor mounted on it. The shielding will largely cause a reduction in the strength and potentially the quality of the 5G signals being received by the sensor. Attenuation of the signal strength can happen through absorption or reflection. The materials that construct the body of the drone (carbon-fiber and plastics) will absorb some of the electromagnetic energy of the 5G signals. The absorption will convert the signal energy into heat in the drone structure and thus attenuate the signal power received by the sensor. Printed Circuit Boards, carbon-fiber and other materials can cause reflections of the incident 5G waves. These reflections deflect the signals away from the sensor, decreasing the energy incident on it. Diffraction and scattering can also occur when the four motor arms, the landing poles, propellers, and other components of the drone can cause the 5G signals to diffract (bend around the edges) and scatter in different directions. The effect of scattering reduces the direct route of the signal to the sensor and can introduce multipath interference (where the sensor gets the identical signal over multiple paths with different delays). The body of the drone can not only cause diffraction and scattering but can also block the direct line of sight between the 5G signal source (e.g., a base station) and the sensor. A clear line of sight is usually optimum for good signal reception, especially at higher 5G frequencies (where higher frequency waves like mmWaves are more susceptible to blockage and absorption).

To assess and quantify the effects of reflections, diffractions, scattering, and absorption, both the drone equipped with the 5G sensor and the 5G sensor alone will be tested in a semi-anechoic chamber. A signal generator will transmit a selected frequency, corresponding to one of the central frequencies used by the four major service providers in Belgium. Each frequency will be emitted at two different attenuation levels (15 dBm and 18 dBm) from the signal generator. The received power values from both experiments (one with the 5G sensor mounted on the drone and the other with only the 5G sensor) will be plotted together for the same emitted frequency and attenuation levels. This comparison will help identify which parts of the drone contribute to shielding effects.

4.2.1 Measurement setup

[Figure 4-8a](#) illustrates the measurement setup used for the drone during the shielding experiments, while [Figure 4-8b](#) presents the configuration for the standalone 5G sensor, as detailed in [Section 3.4.3](#).

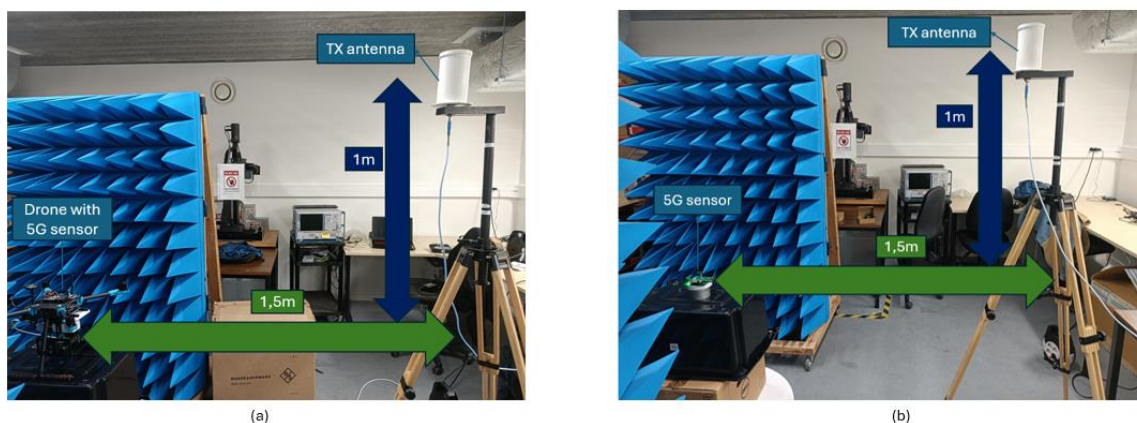


Figure 4-8: The shielding measurement setup for the drone, equipped with the 5G sensor at a horizontal distance of 1.5m from the TX antenna and at a relative height difference of 1m. (a) The 5G sensor without the drone in the same position (b)

4.2.2 Shielding results

The [Appendix](#) includes the results for all frequencies in appendices from [Figure A-1](#) until [Figure A-14](#), here only the highlights will be discussed. [Figure 4-9a](#) displays the received power P_r measured by the 5G sensor at an emitted frequency of 3.750 GHz, with the signal generator set to 15 dBm output power and accounting for a cable loss of 1.74 dB, resulting in an effective attenuation of 13.26 dBm. Each axis from the triaxial sensor is plotted in a different colour and the dashed line represents the 360° counterclockwise rotation. It can be seen that the received power varies between -36.23 dBm until -55.53 dBm for the X-axis, -37.40 dBm until -57.73 dBm for the Y-axis and -40.98 dBm until -59.73 dBm for the Z-axis. There variation in received power depends on the angle α .

[Figure 4-9b](#) shows the received power P_r measured by the standalone 5G sensor at the frequency of 3.750 GHz, with an effective attenuation of 13.26 dBm applied by the signal generator. The received power is plotted separately for each axis (X, Y, and Z) using distinct colors, while the dashed lines represent the full 360° counterclockwise rotation of the sensor. The measurements indicate that the received power varies between -36.73 dBm and -53.13 dBm for the X-axis, -33.73 dBm and -57.73 dBm for the Y-axis, and -35.40 dBm and -62.73 dBm for the Z-axis. To differentiate between variations caused by the directional sensitivity of the 5G sensor and those resulting from electromagnetic shielding effects, the comparisons between their received power P_r is plotted per axis in [Figure 4-10](#), enabling a direct evaluation of the drone's shielding influence.

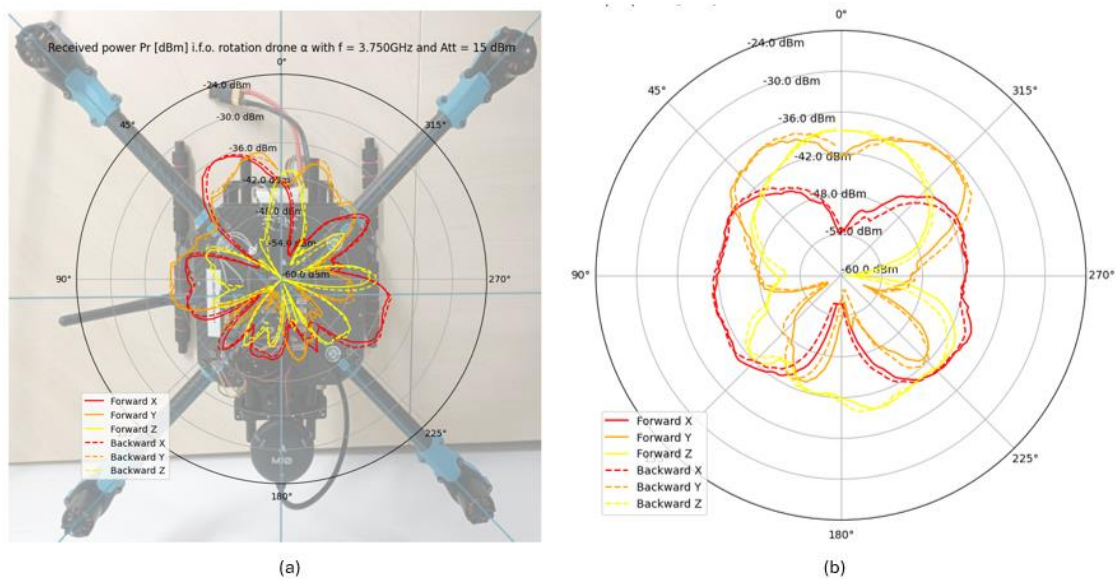


Figure 4-9: Received power P_r in [dBm] in function of the rotation angle α of the incident power by the TX antenna for the drone and 5G sensor at $f = 3.750\text{GHz}$ and $\text{Att} = 13.26\text{ dBm}$ (a) Received power P_r in [dBm] in function of the rotation angle α of the incident power by the TX antenna for the standalone 5G sensor at $f = 3.750\text{GHz}$ and $\text{Att} = 13.26\text{ dBm}$ (b)

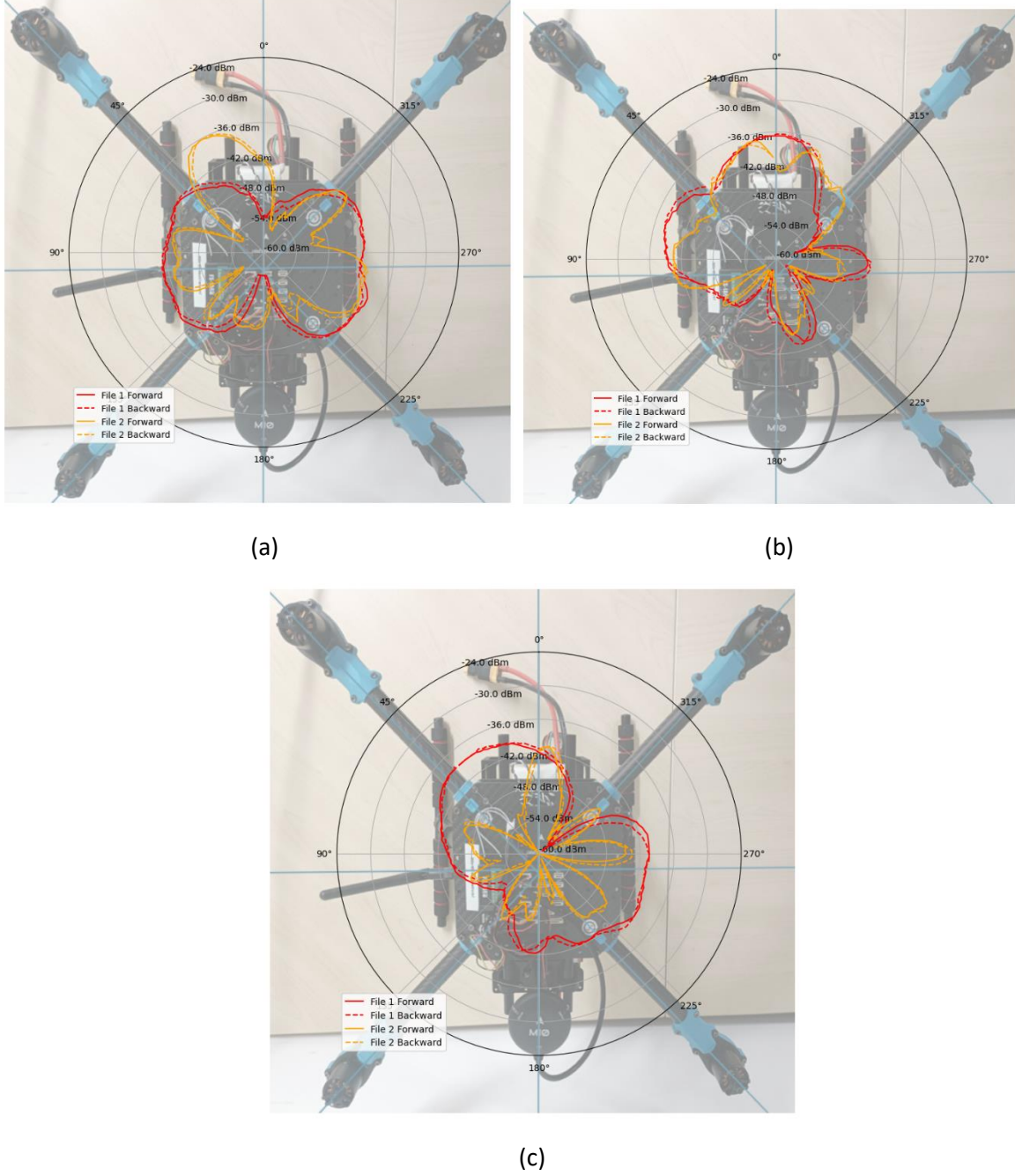


Figure 4-10: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.750\text{GHz}$ and $Att = 13.26\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)

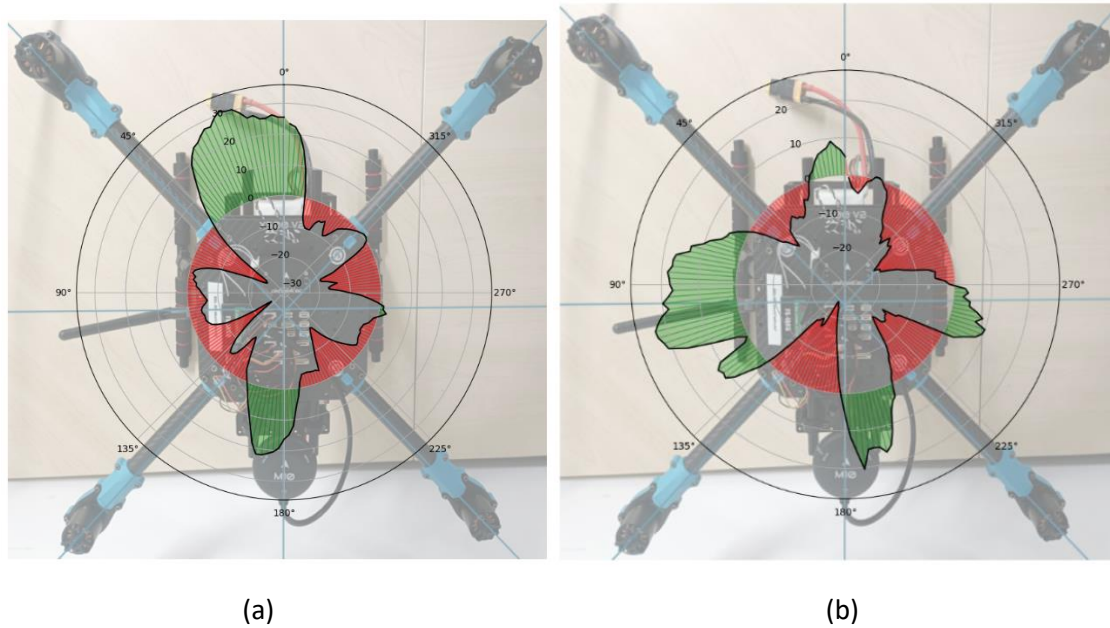
These plots exhibit high sensitivity to even minor spatial variations or slight shifts in angle. Upon analysing [Figure 4-10b](#) , an angle shift of approximately 42° was identified between the experiment involving the drone and the 5G sensor, compared to the standalone 5G sensor. The angle shift has been corrected in all three plots. To quantify the shielding effects, a shielding percentage (SP) is calculated for every angle of rotation α on the turntable. This percentage represents the ratio of the received power $P_{r,drone+sensor}$ with the sensor mounted on the drone to the received power $P_{r,sensor}$ measured with the standalone sensor.

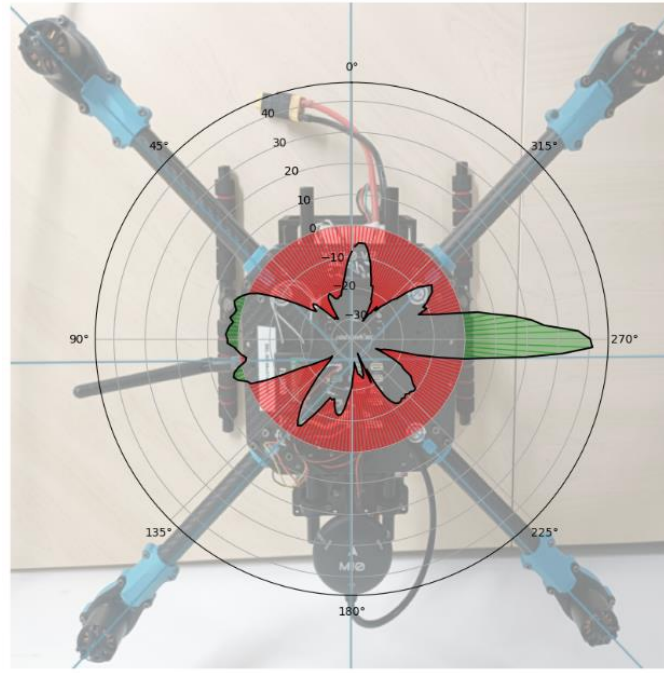
$$SP_{axis}(\alpha) = \frac{P_{r,drone+sensor}(\alpha) - P_{r,sensor}(\alpha)}{P_{r,sensor}(\alpha)} \cdot 100\% \quad (4.2)$$

Where:

- $P_{r,drone+sensor}(\alpha)$ is the received power by the 5G sensor on the drone at angle α [W]
- $P_{r,sensor}(\alpha)$ is the received power by the standalone 5G sensor at angle α [W]
- $SP_{axis}(\alpha)$ is the shielding factor at angle α [%]

[Figure 4-11](#) illustrates the shielding percentages obtained from the experiments conducted at the frequency of 3.750 GHz and an attenuation setting of 13.26 dBm. For the X-axis a power amplification can be observed in sectors: $347^\circ - 47^\circ$ and $157^\circ - 189^\circ$, where SP reached a maximum of +31.04% at 20° . This is likely the result of a combination of electromagnetic and geometric effects related to the drone's mechanic structure. Constructive interference may occur due to reflections from drone components in these two sectors, effectively enhancing the received signal in these sectors. Additionally, conductive materials within the drone can act as secondary radiators, reradiating incident electromagnetic energy and contributing to localized amplification. Multipath propagation, where reflected and direct paths combine constructively, can also reinforce the signal at specific angles. Conversely, the signal was attenuated in sectors: $47^\circ - 157^\circ$, $189^\circ - 255.0^\circ$ and $263.0^\circ - 347.0^\circ$. The highest signal attenuation occurred at 126° with an SP of -26.57% near the lower left motor arm. The upper left and lower right motor arms created the second and third largest shielding effects. Along the Y-axis, the highest amplification was found at 104° with an SP of +23.10%, while the highest attenuation with SP of -24.25% was found at 158° . The upper right, lower right and lower left motor arms are the major sources of attenuation. For the Z-axis, the signal was predominantly attenuated across nearly all rotation angles except in sectors: $67^\circ - 97^\circ$ and $259^\circ - 283^\circ$. The highest attenuation was recorded at 202° of -31.39% . The cause of amplification of 41.03% at 268.0° remains unknown.





(c)

Figure 4-11: Shielding percentage SP for $f=3.750\text{GHz}$ and $Att = 13.26 \text{ dBm}$ for the x-axis (a), y-axis (b) and z-axis (c) The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.

Shielding experiments were performed at centre frequencies of 3.455 GHz, 3.530 GHz, 3.650 GHz, and 3.750 GHz, each tested under two attenuation levels: 15 dBm and 18 dBm. These frequencies correspond to the primary carriers operating in the n78 5G band in Belgium. Table 4-5 summarizes the mean shielding percentage for each frequency–attenuation combination. This value was obtained by averaging the shielding percentages across all angles over a full 360° rotation, for each of the X, Y, and Z axes. The final reported shielding percentage represents the average across these three spatial axes.

$$\overline{SP_{axis}} = \frac{1}{N} \sum_{\alpha=1}^N SP_{axis}(\alpha) \quad (4.3)$$

Where:

- N is the number of measured angles α (this is 360 for one full rotation)
- “axis” $\in \{X, Y, Z\}$
- $\overline{SP_{axis}}$ is the mean shielding factor calculated based on N measured angles

$$\overline{SP_{total}} = \frac{1}{3} (\overline{SP_x} + \overline{SP_y} + \overline{SP_z}) \quad (4.4)$$

The results clearly demonstrate a frequency-dependent shielding effect, with shielding efficiency varying across the tested frequency bands. The lowest mean shielding percentage was observed at 3.650 GHz with an attenuation of 13.28 dBm, yielding a value of -3.46% . When averaging the shielding percentages across all frequency–attenuation combinations for each spatial axis, the Z-axis exhibited the highest average shielding at -11.69% . This may be attributed to the physical placement of the Z-axis antenna, which is located adjacent to the right landing gear pole and is likely subject to increased obstruction from the drone’s mounting structure. Additionally, a consistent trend was observed wherein higher attenuation levels (i.e., higher emitted signal strengths) resulted in slightly greater

shielding percentages. This suggests that stronger incident signals are marginally more affected by structural interference than weaker ones. This trend can be explained by the increased electromagnetic interaction between the incident wave and the drone's structure at higher field strengths. Stronger signals are more likely to induce secondary effects such as enhanced reflections, reradiation, and diffraction around conductive components, amplifying the overall shielding effect. Additionally, structural materials and assemblies may exhibit a slightly nonlinear electromagnetic response, whereby their attenuation characteristics become more pronounced under higher incident field intensities. These factors together contribute to the observed increase in shielding percentage at higher transmission powers.

Frequency [GHz]	Attenuation [dBm]	Shielding x-axis [%]	Shielding y-axis [%]	Shielding z-axis [%]	Shielding [%]
3.455	13.03	-10.91	-10.46	-15.20	-12.19
3.455	15.81	-10.81	-10.14	-15.84	-12.26
3.530	13.20	-5.22	-5.17	-9.29	-6.56
3.530	16.14	-4.95	-5.44	-10.36	-6.92
3.650	13.28	1.04	-3.34	-8.07	-3.46
3.650	16.14	1.37	-3.55	-9.68	-3.95
3.750	13.26	-1.60	-2.29	-11.88	-5.26
3.750	16.18	-2.58	-2.16	-13.19	-5.98
Average:		-4.21	-5.32	-11.69	-7.07

Table 4-5: Mean shielding percentage (SP) for all frequencies and attenuation of 15dBm and 18dBm

4.3 The drone's Antenna Factor (AF)

4.3.1 Measurement setup

Finding the antenna factor of the sensor mounted on the drone is crucial to be able to determine the electric field strength as described in [Section 1.3.4.1](#). [Figure 4-12](#) shows the measurement setup to define the antenna factor with the Narda SRM 3006. In this configuration, the Narda SRM-3006 replaced the drone and was positioned 1.5 meters from the TX antenna, with a relative height difference of 1 meter. The turntable was first rotated clockwise through 360°, followed by a counterclockwise rotation through 360°, at a constant angular velocity of 2°/s. This resulted in a total measurement duration of 6 minutes, allowing sufficient time to record both the maximum and average electric field strength. The same centre frequencies (3.455 GHz, 3.530 GHz, 3.650 GHz, and 3.750 GHz) were targeted to ensure consistency with the shielding experiments. This enabled a direct comparison of measured power levels and the subsequent calculation of the antenna factor for each frequency.

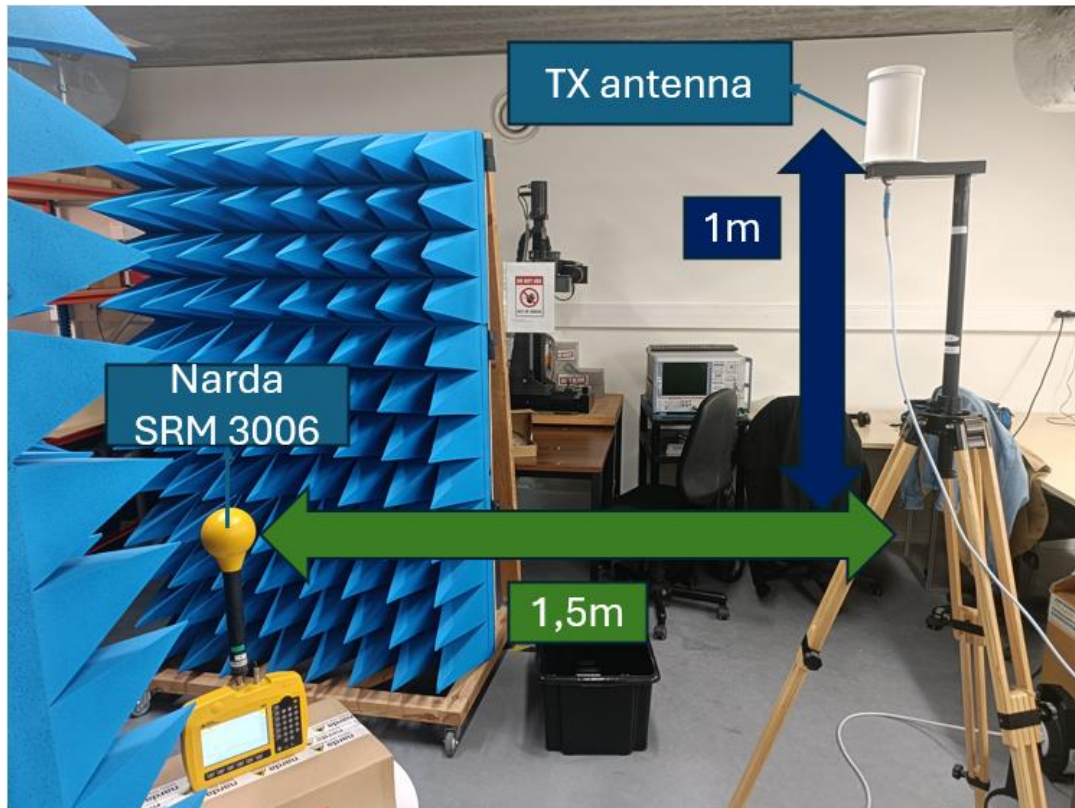


Figure 4-12: The measurement setup to determine the antenna factor with the Narda SRM 3006

4.3.2 Antenna factor results

[Table 4-6](#) shows the calculated antenna factors in $[1/m^2]$ and the measured maximum electric field E_{max} [V/m] and the average electric field E_{avg} [V/m]. As the frequency further increases the antenna factor reduces. The highest antenna factor of $0.000409 \text{ } 1/m^2$ was found at 3.530 GHz. [Figure 4-13](#) shows a plot of the antenna factor in function of the frequency. The measurements in the field will be taken at the frequency of 3.530 GHz, the average of two Antenna Factors for that frequency is 0.000396. The lowest Antenna Factor at 3.750 GHz indicates that the antenna is the most sensitive at this frequency and that smaller electric field will induce larger RMS output detector voltages, improving measurement precision and detection capability. Lower frequencies (like 3.455 GHz) propagate slightly better in open environments.

Frequency [GHz]	Attenuation [dBm]	E_{max} [V/m]	E_{avg} [V/m]	Antenna Factor $[1/mm^2]$
3.455	13.03	0.91	0.69	312.34
3.455	15.81	0.70	0.51	349.03
3.530	13.20	1.037	0.69	408.70
3.530	16.14	0.74	0.48	383.46
3.650	13.28	1.07	0.81	203.48
3.650	16.14	0.76	0.58	203.89
3.750	13.26	0.88	0.63	115.60
3.750	16.18	0.56	0.46	119.69

Table 4-6: AF in function of different frequency-attenuation combinations

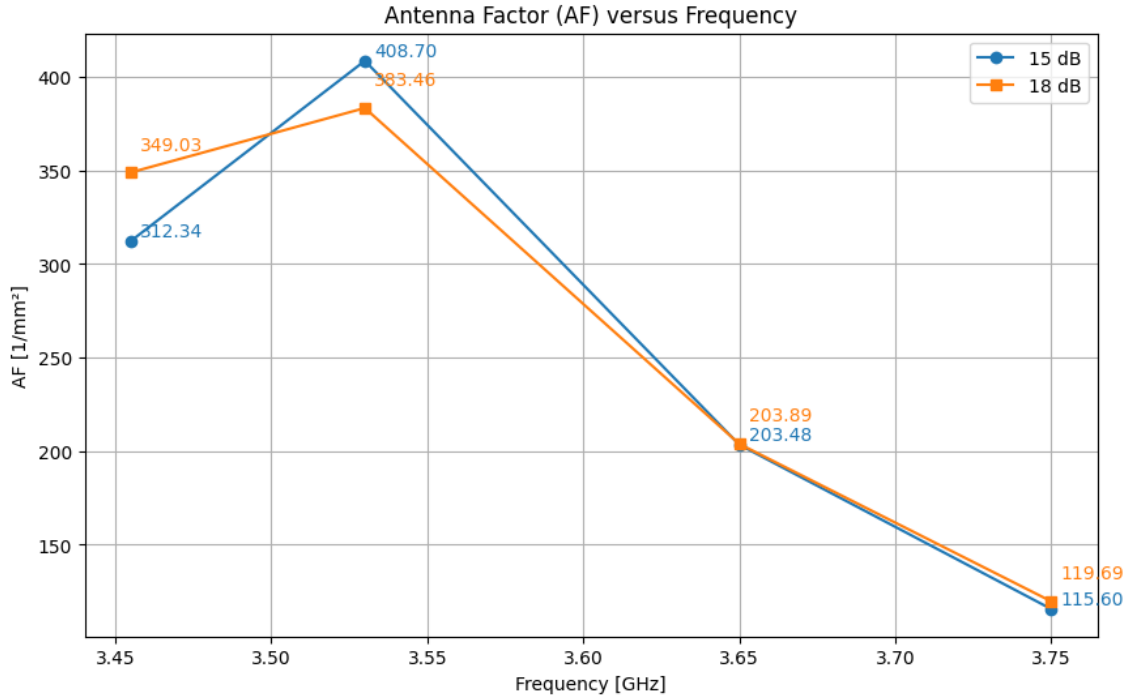


Figure 4-13: Antenna Factor in function of the frequency

4.4 In situ measurement campaign

4.4.1 Measurement setup

[Figure 4-14](#) illustrates the in situ measurement setup. During the measurement campaign, the drone follows a flight path consisting of 16 waypoints, hovering for 10 seconds at each location. At a rate of one reading per second, the sensor records a total of 10 measurements per waypoint, with each individual measurement derived from approximately 25.000 samples, the total received power P_{tot} is computed as the root sum of squares (RSS) of the average power (in watts) measured along the X, Y, and Z axes. The corresponding total power density S_{tot} is calculated by dividing the by the antenna factor (AF) corresponding to the transmission frequency of 3.530 GHz. Finally, the total electric field strength E_{tot} is obtained by multiplying S_{tot} by Z_0 , the intrinsic impedance of free space.

$$P_{tot} = \sqrt{\left(\frac{1}{n} \sum_{i=1}^n P_{x,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{y,i}\right)^2 + \left(\frac{1}{n} \sum_{i=1}^n P_{z,i}\right)^2} \quad (4.5)$$

$$S_{tot} = \frac{P_{tot}}{AF} \quad (4.6)$$

$$E_{tot} = \sqrt{S_{tot} \cdot Z_0} \quad (4.7)$$

Where:

- P_{tot} is Total received power [W]
- S_{tot} is Total power density [W/m²]
- AF is Antenna factor from 3.530 GHz [1/m²]
- E_{tot} is Total electric field [V/m]

The 16 waypoints were positioned at a distance of 6.10 m from the transmitting (TX) antenna. This distance was determined through a preliminary test flight. The TX antenna was mounted at a height of

2.36 m above ground level. The vertical measurement grid began at a height of 2.00 m, with each subsequent waypoint spaced 1.50 m horizontally and 1.00 m vertically from the previous one. This configuration resulted in a total grid area of 13.5 m² where the heat map would be constructed. The grid was designed to enable the analysis of changes in the average electric field strength (E_{avg}) across specific segments. In particular, it allows for evaluating potential changes in E_{avg} between waypoint groups 1–4, 5–8, 9–12, and 13–16. Notably, waypoints 1, 5, 9, and 13 are aligned directly with the TX antenna, they can be useful to evaluate the potential changes in E_{avg} with increasing altitudes.

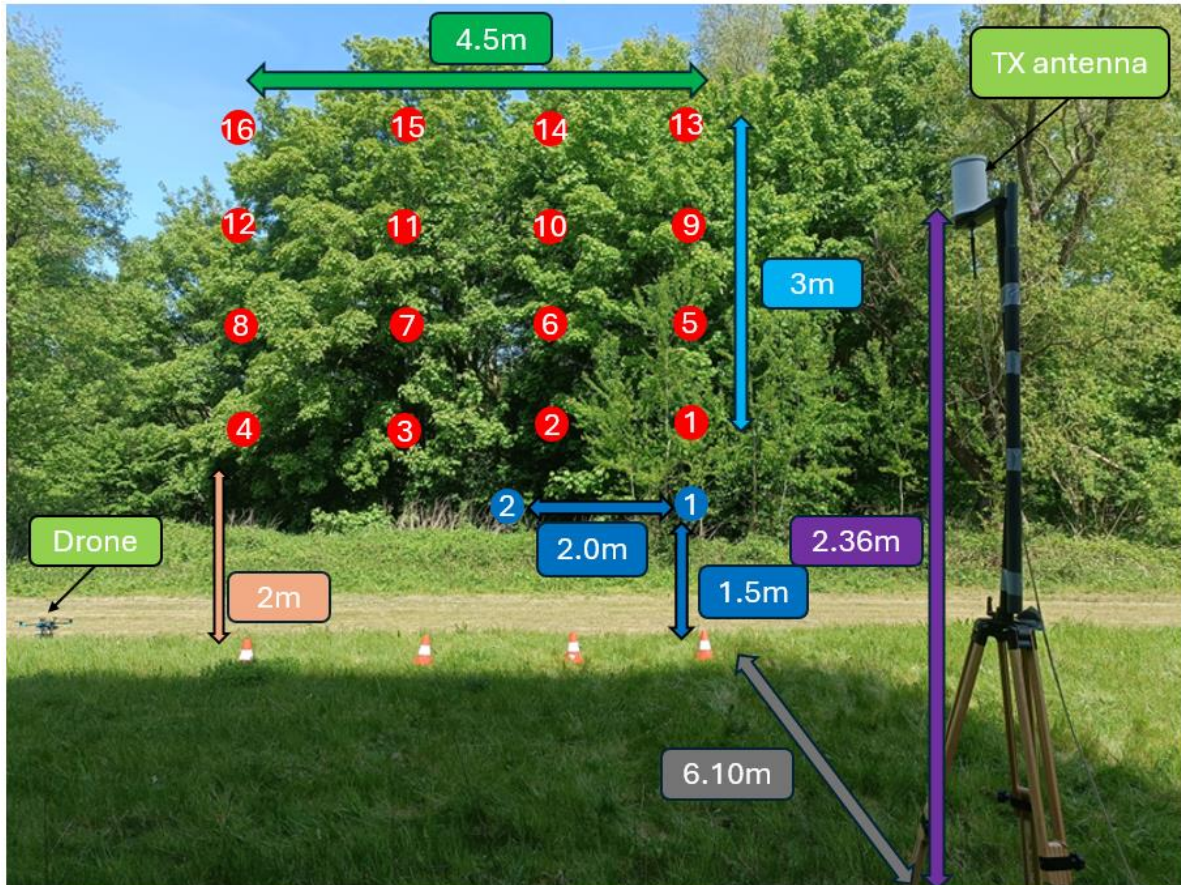


Figure 4-14: The red markers in the figure indicate the 16 predefined drone waypoints, which form a structured vertical measurement grid. Each waypoint is spaced 1.5 m apart horizontally, starting at a height of 2.0 m. Successive rows in the vertical direction are offset by 1.0 m, resulting in a three-dimensional grid covering a total area of 13.5 m². These points represent the positions at which RF-EMF measurements were collected by the drone. The two blue markers indicate the locations of broadband electric field measurements performed with the Narda NBM-550 field strength meter. The TX antenna was positioned at a lateral distance of 6.10 m from the waypoint grid and mounted at a height of 2.36 m above ground level.

4.4.2 In situ measurement results

To assess the average electric field strength E_{avg} at a distance of 6.10 m from the TX antenna, two broadband measurements were performed using the Narda NBM-550 field strength meter. The first measurement, taken at a height of 1.50 m and a horizontal distance of 6.10 m from the TX antenna, resulted in an E_{avg} value of 1.83 V/m. A second measurement was conducted 2.00 m to the left of the initial location, at the same height, yielding a slightly lower E_{avg} of 1.70 V/m. 2 m more to the left from the previous measurement location. In [Figure 4-14](#) the two measurement locations are marked by the blue waypoints. These results demonstrate a decrease in electric field strength as the distance from the TX antenna increases laterally, which aligns with expectations due to field attenuation with distance.

4.4.3 Exponential kriging

Exponential kriging is a geostatistical interpolation technique suitable for estimating the E-field between the 16 measured waypoints. RF EMF fields often exhibit spatial autocorrelation. This means that measurements taken at locations closer to each other have similar exposure values and vary less than those taken further apart. Exponential kriging methods explicitly account for spatial autocorrelation, leading to more accurate and reliable interpolations compared to simpler methods that assume spatial independence. Autocorrelation be proven by the equation found by Maxwell et al.:

$$\nabla^2 E - \left(\frac{1}{c^2}\right) \frac{\partial^2 E}{\partial t^2} = 0 \quad (4.8)$$

Where:

- ∇^2 is the Laplacian operator (describes spatial variation)
- E is the electric field vector [V/m]
- C is the speed of light [m/s]
- t is time [s]

If the electric field at a particular point changes with time ($\frac{\partial^2 E}{\partial t^2} \neq 0$), this change necessitates a corresponding spatial variation ($\nabla^2 E \neq 0$) in the field in the surrounding space to satisfy the equation. When the electric field strength at a point is different from the average of the field at its neighbours ($\nabla^2 E \neq 0$), it implies a spatial gradient or curvature in the field. This equation highlights that the electric field at one point in space influences the electric field at its neighbouring points, because it propagates as a wave. Also the field doesn't change abruptly from one point to another infinitesimally close point, it varies smoothly and is intrinsically linked to the temporal evolution of the field.

The strength of the E-field is fundamentally related to the distance from the source. For a simple TX antenna like the one used in the experiment in free space, the electric field strength decreases with the inverse square of the distance. This decrease in strength with an increase in distance to the emitting source is linked to the effects of absorption, reflections, scattering, diffraction and path loss.

$$E \sim \frac{1}{r^2} \quad (4.9)$$

Where:

- E is the electric field strength [V/m]
- r is the distance to the RF EMF source [m]

Exponential kriging utilizes an underlying exponential variogram to model the spatial dependence of the electric field (E-field) measurements. This variogram quantifies the dissimilarity between E-field values as a function of the distance separating the measurement locations (waypoints). Specifically, the spatial dependence is modelled to decrease as the distance between the waypoints increases, eventually reaching a maximum semivariance (the sill) beyond a certain range. The process involves calculating the squared difference between the E-field values at all pairs of waypoints and relating these differences to the Euclidean distance ($|h|$) between the pairs. An exponential variogram model is then fitted to these calculated values using the following equation:

$$\gamma(h) = \sigma^2 \left(1 - e^{\frac{-|h|}{a}}\right) + \tau^2 \quad (4.10)$$

Where:

- $\gamma(h)$ is the the semivariance at given Euclidian distance h between two waypoints $[(V/m)^2]$
- σ^2 is the partial sill, indicating the component of the variance that is spatially dependent $[(V/m)^2]$
- a is the range parameter, representing the distance beyond which the spatial autocorrelation becomes practically negligible [m]
- $|h|$ is the Euclidean distance between two waypoints [m]
- τ^2 is the nugget variance, accounting for measurement error or microscale variability that is not spatially correlated at the sampled distances $[(V/m)^2]$

To estimate the E-field at an unmeasured location, a system of linear equations is formulated. This system utilizes the fitted exponential variogram to determine the optimal weights assigned to each of the 16 measured waypoints. The weights are chosen such that the estimate is unbiased and the estimation variance is minimized. The kriging equation for estimating the E-field E at a location x_o based on 16 E-field values $E(x_i)$ is:

$$E(x_o) = \sum_{i=1}^{16} \lambda_i E(x_i) \quad (4.11)$$

Where:

- $E(x_o)$ is the etimated electric field at location x_o [V/m]
- $E(x_i)$ is the measured electric field at one of the 16 waypoints [V/m]
- λ_i is the weight assigned to each measurement determined by the exponential variogram equation

4.4.4 M10 GPS accuracy

The grid was designed with an approximate waypoint spacing of 1.50 meters. Minimizing the distance between waypoints was essential to improve the resolution of the exposure heat map. However, some challenges were encountered with the accuracy of the M10 GPS. During waypoint navigation, the Holybro X500 V2 utilizes EKF3 sensor fusion to maintain precise positional awareness. This system integrates data from the GPS for position, the IMU for acceleration and angular velocity, and the barometer for altitude. The EKF3 sensor fusion allows the drone to maintain an accurate separation of 1.50 meters between consecutive waypoints. Nonetheless, a residual positional offset during the drone's liftoff introduces slight position shifts in the waypoints, resulting in minor discrepancies compared to previous flight sessions.

A measure to quantify the accuracy of GPS systems is the Circular Error Probable (CEP). The M10 GPS has a CEP of 2.0m, which means that the GPS readings will fall within a circle radius of 2.0 m around the true location. In simpler terms if you take many position readings with your GPS, half of those readings will be no more than 2.0 m away from your actual position. The other half will be further away than 2.0 m. The errors in the horizontal plane (latitude and longitude) are assumed to be normally distributed. When you combine two independent normal distributions the resulting distribution of the position errors is a circular bivariate normal distribution. [Figure 4-15](#) shows this distribution. For bivariate normal distribution with zero mean and equal variances, the radial errors follows a Rayleigh distribution. The relationship between CEP and the standard variance σ is:

$$CEP = \sigma \sqrt{2 \ln(2)} \approx 1.1744 \sigma \quad (4.12)$$

$$\sigma = \frac{CEP}{\sqrt{2 \ln(2)}} = \frac{2.0 \text{ m}}{1.1744} = 1.699 \text{ m}$$

For a Rayleigh distribution the chance that a point falls between a radius r is defined by:

$$P(r) = 1 - e^{-\frac{r^2}{2\sigma^2}} \quad [24]$$

$$P(2\sigma) = 1 - e^{-2} = 86.47\%$$

$$P(3\sigma) = 1 - e^{-\frac{9}{2}} = 98.89\%$$

Although a shift in the overall waypoint locations occurred between flights, the consistent 1.50 m spacing between consecutive waypoints was maintained. Consequently, direct comparison of the E-field measurements at the exact same geographic coordinates across different flights is not feasible. However, the general spatial trend of the RF-EMF exposure across the monitored area remains comparable.

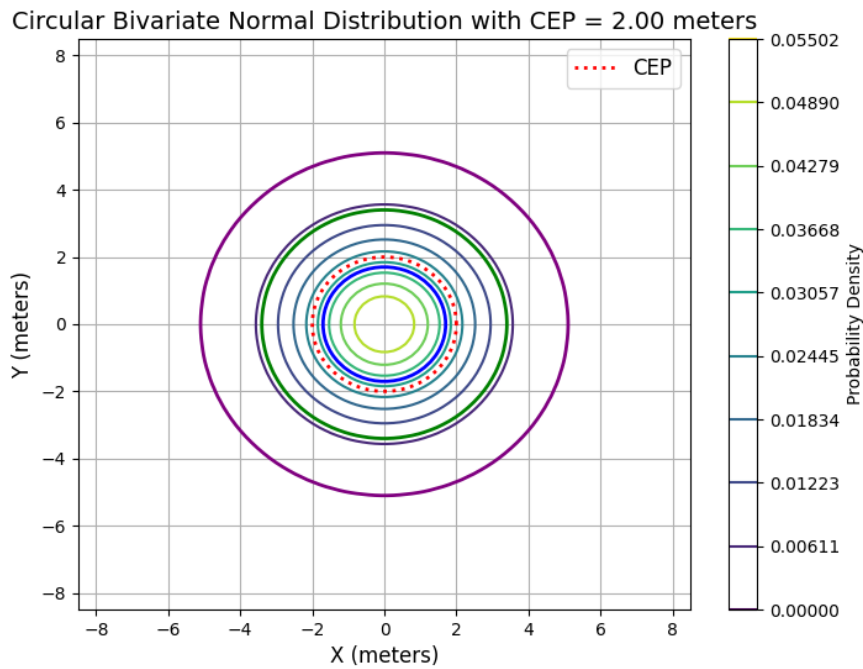


Figure 4-15: Circular Bivariate Normal Distribution for longitude (X) and latitude (Y) with CEP = 2.0 m

4.4.5 2D vertical grid exposure heat map

[Figure 4-16](#) shows the heatmap from the first flight. The heatmap clearly demonstrates that the exposure is not uniform across the waypoints. A prominent area of high E-field strength (indicated by the red and yellow colors) is observed near waypoints 1, 2, 5 and 9. These were the waypoints that were in line with the TX antenna and with minimal horizontal displacement relative to the antenna (see [Figure 4-14](#)). The peak E-field value reached around 3.83 V/m near waypoint 5 at a height of 3 m. Conversely there are areas of significantly lower E-field exposure (indicated by blue and green colors), particularly in the bottom-left corner and extending towards higher heights on the left side and towards the middle. The lowest measured value was 1.75 V/m in waypoint 4 at a height of 2 m. The E-field strength generally decreases as the distance from the TX antenna increases, which is typical behaviour for RF EMF fields. At the coordinate corresponding to the broadband probe location, the measured

electric field strength using the broadband NBM-550 meter was 1.83 V/m. In contrast, the electric field strength interpolated at the same location using Kriging applied to the 5G sensor data grid yielded a value of approximately 2.85 V/m, indicating a discrepancy of 1.02 V/m between the two measurement systems. For the second broadband measurement point, located approximately 2 m further to the left, the broadband meter recorded a value of 1.70 V/m, whereas the Kriging-interpolated value from the 5G sensor data at that exact coordinate was 2.74 V/m—resulting in a 1.04 V/m difference. These deviations suggest systematic differences in sensitivity to E_{avg} between the broadband and 5G sensor. [Figure 4-17](#) presents the E-field heatmap obtained from the second flight. Due to limitations in the drone's GPS accuracy, the vertical waypoint grid was displaced by approximately 4.5 meters to the right during the second flight, resulting in the entire grid being positioned along the positive x-axis, whereas it was located along the negative x-axis during the first flight. The position of the transmitting antenna remained fixed throughout both measurement campaigns. The region of highest electric field exposure is now observed near waypoints 4, 8, and 12, with a peak value of 4.25 V/m recorded at waypoint 4. The displacement of waypoints to the right, relative to their planned positions, is attributed to the positional inaccuracy of the M10 GPS module, as discussed in [Section 4.4.4](#). This shift was also visually confirmed through analysis of the drone flight recording. A detailed comparison between the two flight datasets is not feasible due to these positional discrepancies and will therefore not be conducted. The area exhibiting the lowest E-field strength was identified around waypoints 2, 3, and 13, with a minimum value of 1.96 V/m at waypoint 13. Notably, the field gradients surrounding the hotspot appear steeper than in the first flight, indicating sharper spatial variations in E-field intensity.

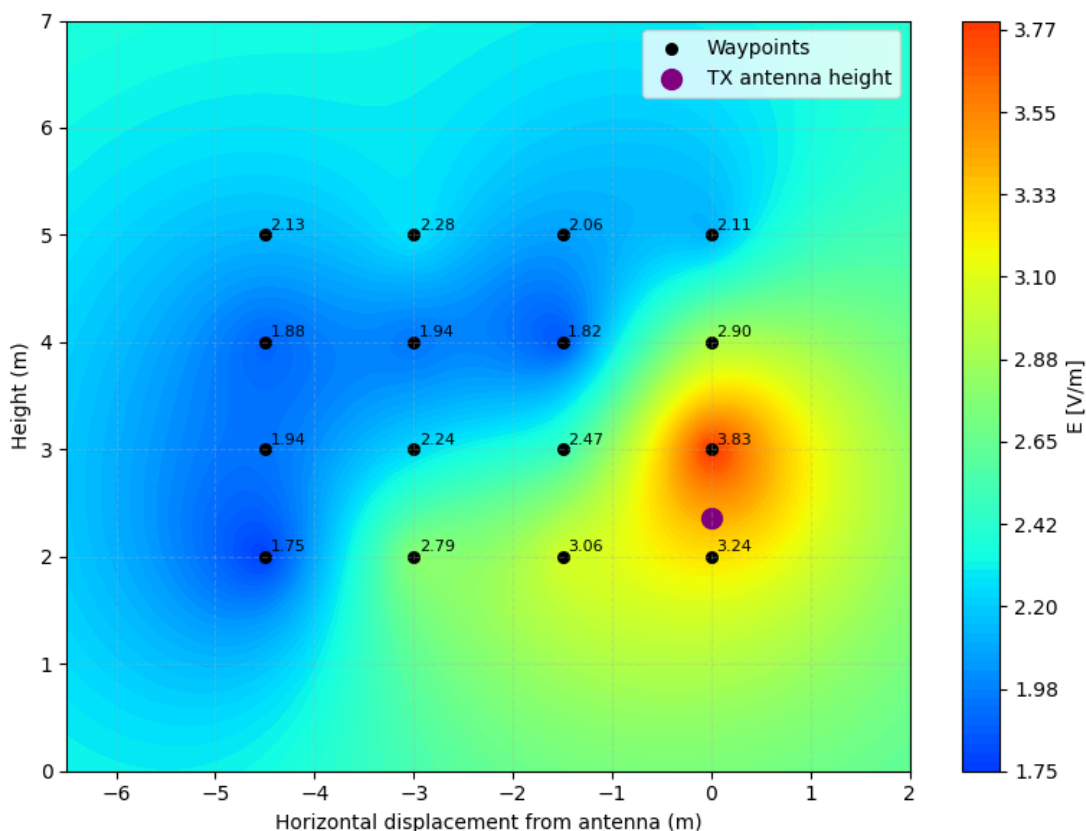


Figure 4-16: Interpolated field of E_{avg} using exponential kriging during the first flight. The vertical grid is constructed left of the TX antenna, which location is marked by the purple dot on the heat map. The location of maximum RF-EMF exposure coincides with the position of the TX antenna, specifically between waypoints 1 and 5.

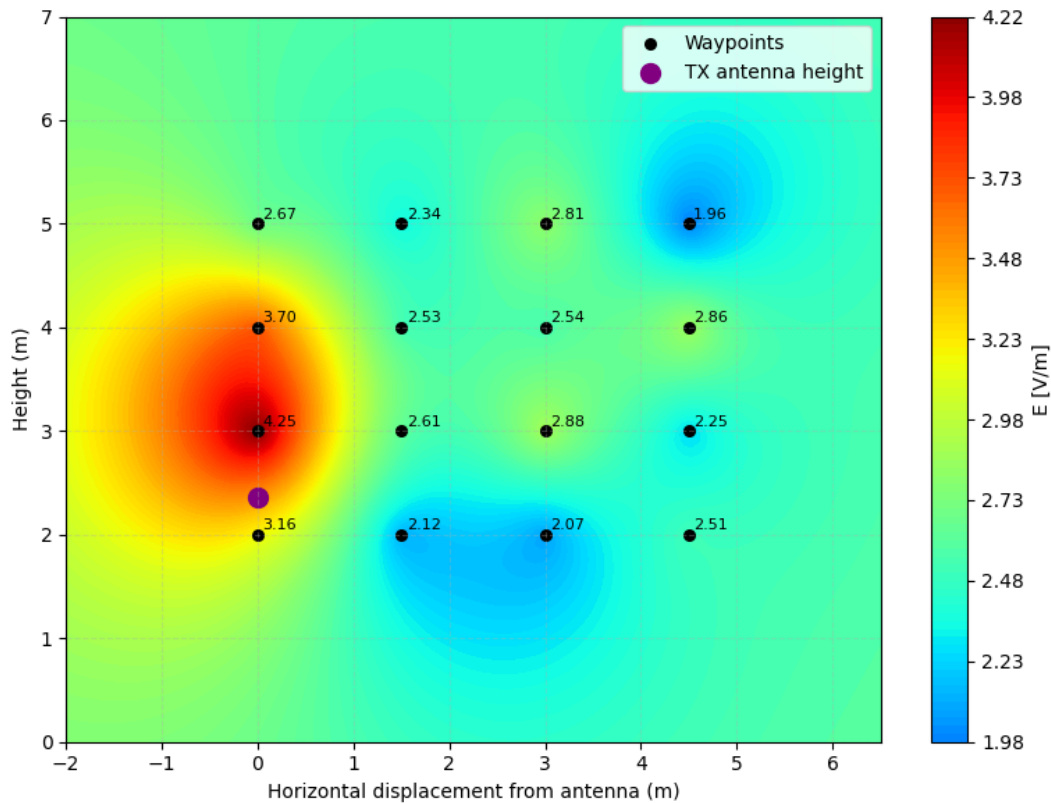


Figure 4-17: Interpolated field of E_{avg} using exponential kriging during the second flight. The vertical grid is constructed to the right of the TX antenna, which location is marked by the purple dot on the heat map. The location of maximum RF-EMF exposure coincides with the position of the TX antenna, specifically between waypoints 1 and 5.

5. Future work

5.1.1 Increasing position accuracy

As mentioned in [Section 4.4.4](#) the M10 GPS has its limitations on its positional accuracy. With a CEP of 2.0 m only 50% of the drone's position estimates will be within a radius of 2.0 m. In order to be able to compare measurements across several flights and achieve reliable reproducibility another GPS system will need to be used called a Real-Time-Kinematics (RTK) gps. [Figure 5-1](#) shows the Here3 RTK gps (on the right side) and Here+ base station (on the left side), these devices form a high-precision Global Navigation Satellite System (GNSS) primarily used on robotics and drones or other autonomous vehicles for accurate positioning. It is designed to work with a Pixhawk flight controller and is native to the Ardupilot ecosystem, which was used on the Holybro X500 V2 drone. An RTK GPS has two type of GPS fix statuses. After the takeoff the drone will receive RTK Float accuracy, which means that its position estimates will be accurate between 20 to 50 centimeters. After anywhere between 30 seconds and 2 minutes the drone will receive an RTK fix status, which introduces centimeter-level accuracy around 1 to 2 cm. The Here+ base station uses GNSS signals (simultaneous receipt of GPS L1, GLONASS L1, BeiDou B1 and Galileo E1) to generate RTCM3 correction data, which is transmitted via the 433 MHz telemetry radio link connected to the Pixhawk flight controller. Once received, the Pixhawk forwards these corrections to the Here3 RTK GPS module over the DroneCAN bus operating at a speed of 1 Mbps. Upon receiving these correction messages, the Here3 transitions from RTK Float mode (providing decimeter-level accuracy) to RTK Fix mode, which delivers centimeter-level positional accuracy. This high-precision RTK solution ensures consistent and reproducible drone positioning, critical for comparing measurements across multiple flights. No extra influence will be introduced because the

telemetry connection at 433 MHz is already assembled on the device, however experiments verifying this will still have to be performed [79].



Figure 5-1: Here3 RTK gps [79]

5.1.2 Depth camera for up-close base station measurements

During this thesis the vertical grid was developed by measuring exposure coming from a signal generator assembled with a TX antenna. This signal generator emitted a frequency of 3.530 GHz and mimicked a 5G antenna assembled on a base station. However flying near a base station would introduce new interesting insights into their real RF-EMF exposure upclose and could potentially also reconstruct their beamsteering pattern. That pattern could be monitored by assembling a UE on the drone and attracting a beam towards the UE. That way it the exposure in the centre of the beam and on the edges could be monitored and this could ultimately create a 2D or 3D reconstruction of the 5G beam shape. This implies extra failsafe mechanisms in order to avoid a collision with the base station at all costs. [Figure 5-2](#) shows an Intel RealSense d435 depth camera. The Intel RealSense Depth Camera D435 is a depth camera that relies on stereoscopic vision to provide both depth and RGB data. It employs a pair of infrared (IR) cameras, having a baseline distance between them, to capture alternate views of a scene. An IR emitter projects a pseudo-random pattern to enable correspondence matching between images, more particularly in low-texture areas. The RealSense Vision Processor calculates depth by determining the disparity between corresponding points in the left and right images, which is inversely proportional to depth. The D435 has a depth resolution of up to 1280 x 720 pixels, RGB resolution of up to 1920 x 1080 pixels, and frame rates of up to 90 fps. Having a horizontal field of view of 69.4°, a minimum depth distance of around 0.2 m, and a maximum depth distance of around 10 m, which means that a precise distance between 0.2m until 10m to a base station can be established in an autonomous flight. [Figure 5-3](#) shows a frame out of a video from a 5 minute flight with the Intel RealSense D435 equipped on a drone and communicating with the Jetso TX2 companion computer. The blue areas in the heat map are more up close and the red areas are further away [80].

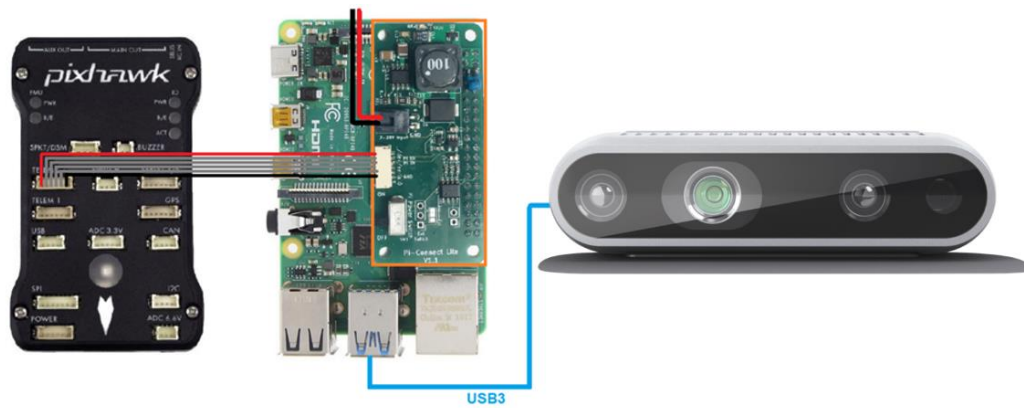


Figure 5-2: Pixhawk connected to a Raspberry Pi and RaspBerri pi connected through a Intel Realsense depth-camera

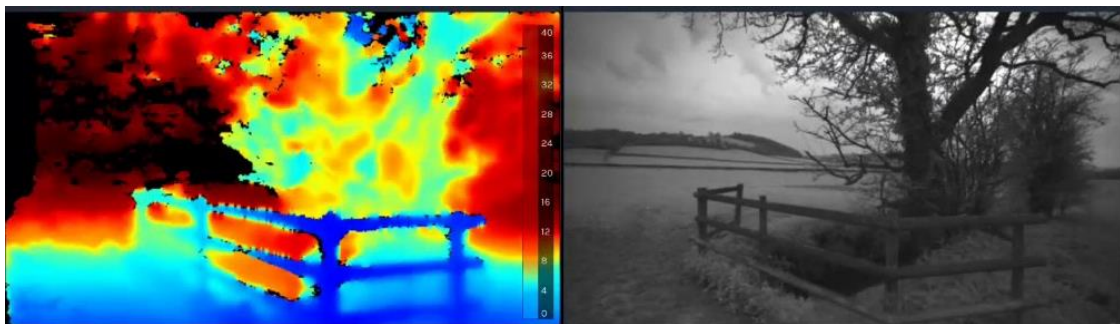


Figure 5-3: Intel RealSense D435 Depth Camera on Jetson TX2 UAV [68]

The Intel RealSense D435 is equipped not only with two image sensors and an integrated infrared projector for depth sensing, but also includes an RGB camera. This RGB camera can be leveraged for object detection, specifically to identify and track a 5G base station antenna. Once detected, the system can continuously monitor the antenna's position and adjust its own location relative to the antenna's centre point. This enables the construction of a vertical scanning grid aligned with the antenna structure. Simultaneously, the system maintains a safe operating distance using real-time depth information, and achieves centimeter-level positioning accuracy through the integration of RTK GPS, as discussed in [Section 5.1.1](#). A yolo v11 model was trained with a training set of approximately 300 labeled images of base station antenna's and achieved great accuracy in tracking base station antennas. [Figure 5-4](#) shows the object recognition of 4 antennas with an average accuracy of 79%. This system should be further optimized into recognizing a visual difference between 5G antennas, which are typically more squared, and other antennas.

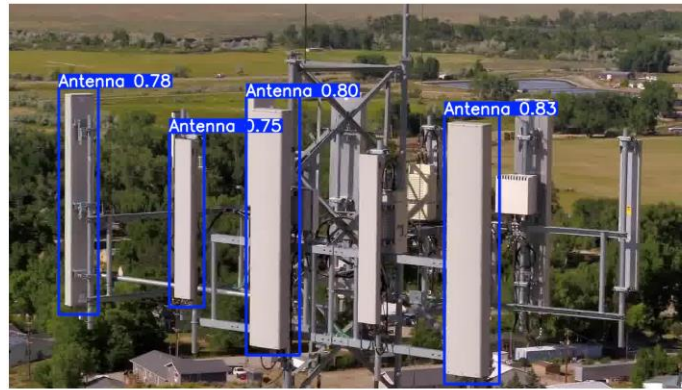


Figure 5-4: Base station antenna recognition using Yolo V11 architecture

Figure 5-5 shows all training results from the yolo v11 model. The box_loss, cls_loss, and dfl_loss (for both training and validation) exhibit a clear downward trend, indicating effective learning and convergence. Although validation losses are slightly more erratic in the early epochs, they stabilize in later stages, suggesting improved generalization. Both precision and recall steadily increase, with recall showing a more significant early jump followed by stabilization. This indicates that the model is increasingly able to correctly identify relevant objects with fewer false negatives and positives. The metrics mAP50(B) and mAP50-95(B) improve substantially over time. The mAP@0.5 rises quickly and levels off above 0.8, while the stricter mAP@0.5:0.95 improves more gradually, demonstrating the model's enhanced localization and classification accuracy at multiple IoU thresholds.

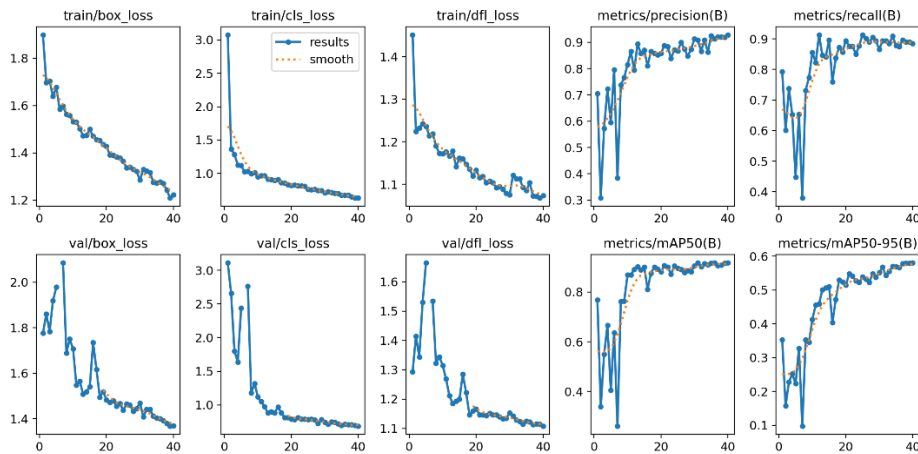


Figure 5-5: Training results from the yolo V11 antenna object detection model

6. Conclusion

This thesis succeeded in developing and testing an autonomous quadcopter system equipped with a triaxial 5G RF-EMF sensor for exposure monitoring in the n78 band used by 5G NR in Belgium. The primary objective was to enhance the efficiency of RF-EMF exposure measurements in the vicinity of 5G base stations by measuring key parameters such as average electric field strength (E_{avg}) and maximum electric field (E_{max}) in three-dimensional space, reducing manual labor and data inconsistency due to human influence.

A comparative study between an Arduino, Pixhawk and JI based model led to the use of the Holybro X500 V2 drone because it is relatively cheap and modular, complemented by a triaxial 5G NR sensor. Detailed calibration processes involving IMU, accelerometer, radio, compass, and notch filtering were performed to ensure a reliable autonomous drone flight. The system was programmed for autonomous flight via a Python-based waypoint navigation system augmented by a Mission Planner waypoint editor so that flexibility and repeatability could be achieved in data collection.

Some of the primary experimental results include the reduction of onboard-electronics interference, reduced by around 3 dB when the 5G sensor is positioned face-up, enhancing measurement accuracy. The drone shielding was quantified and showed frequency- and axis-dependent attenuation with an average shielding of 7.42% across all axes, with the shielding being strongest along the Z-axis due to structural restrictions. The AF was calibrated with a maximum sensitivity of 3.750 GHz to allow accurate conversion of received power by the RMS detectors to electric field strength. Spatial measurements were conducted directly in the field using a 16-waypoint vertical grid located 6.10 m horizontally from a signal generator equipped with a TX antenna. These measurements revealed variations in both average and maximum electric field strength, with the highest average values recorded at the waypoint closest to the TX antenna (3.83 V/m during the first flight and 4.25 V/m during the second). Exponential kriging was applied for interpolation, successfully extracting spatial autocorrelation while retaining small positional errors from the M10 GPS (CEP of 2.0 m).

The results validate drone RF-EMF monitoring by drones as a low-cost and effective method of 5G exposure estimation that offers higher spatial resolution and flexibility compared to traditional approaches. The system's ability to create high-resolution 2D exposure heat maps increases public health transparency and delivers meaningful data for epidemiological studies, which improves the safety of 5G installations within compliance boundaries.

Future work could integrate Real-Time Kinematics (RTK) GPS for centimeter-level positioning accuracy, enhancing measurement reproducibility. Employing depth cameras could enable safe, close-range base station measurements, potentially reconstructing 5G beam patterns. Expanding to mmWave frequencies would broaden applicability. A multi-drone network could facilitate large-scale RF-EMF monitoring. Optimizing drone design to reduce Z-axis shielding would improve accuracy. Finally, leveraging machine learning for real-time antenna detection could streamline autonomous navigation.

Social reflection

The rollout of fifth-generation (5G) wireless networks is an evolution in cellular communications offering unprecedented data capacities, ultra-low latencies, and vast numbers of devices. That said, the public's reaction to the evolution has not been all positive due to continued concerns regarding possible biological impacts of radio-frequency electromagnetic field (RF-EMF) exposure. This master's thesis not only contributes to technical advances in exposure measurement through the development of an autonomous drone for measuring that exposure but also contributes to societal debates on the issue of electromagnetic radiation as well as technology reception.

The social significance of the work resides largely in the potential to increase public trust and transparency. By providing reproducible high-resolution RF-EMF exposure measurements in two or later even three dimensions, the platform allows for more precise environmental monitoring in the neighbourhood of 5G infrastructure. These factual information can be instrumental in dispelling public concerns and encouraging well-informed debate among the public, scientific constituency, and the authorities. In all of this, the system created is not just a research tool but an instrument towards opening up access to confirmable exposure details.

From a health policy point of view, the information gathered through the use of this drone system can be an invaluable tool for epidemiological research and regulatory assessment. As public health recommendations for RF-EMF exposure (such as ICNIRP's guidelines) adapt to new technologies like 5G and upcoming 6G, the need for accurate, high-fidelity measurement technology becomes more and more obvious. The ability to collect information automatically in the proximity of base stations and with minimal human intervention enhances long-term observational strategies and diminishes the logistical impact on research institutes.

The project is also an example of responsible technological innovation. Electromagnetic interference reduction, mechanical shielding, and flight safety were considered in the development of the system to guarantee that the deployed system not only meets scientific purposes but also meets ethical and operational requirements. In addition, the project illustrates the need for collaboration between disciplines—automation, telecommunications, electronics, and environmental health.

In short, the social contribution of this thesis goes beyond its technical merit. It presents an empirically grounded response to issues of the day related to wireless technologies and advances the discourse of informed and engaged public discussions on infrastructure in the digital age, public health, and what the future of cities should become. As 5G continues to build out and 6G appears on the horizon, such research will continue to be critical in informing science-driven policy and public discourse.

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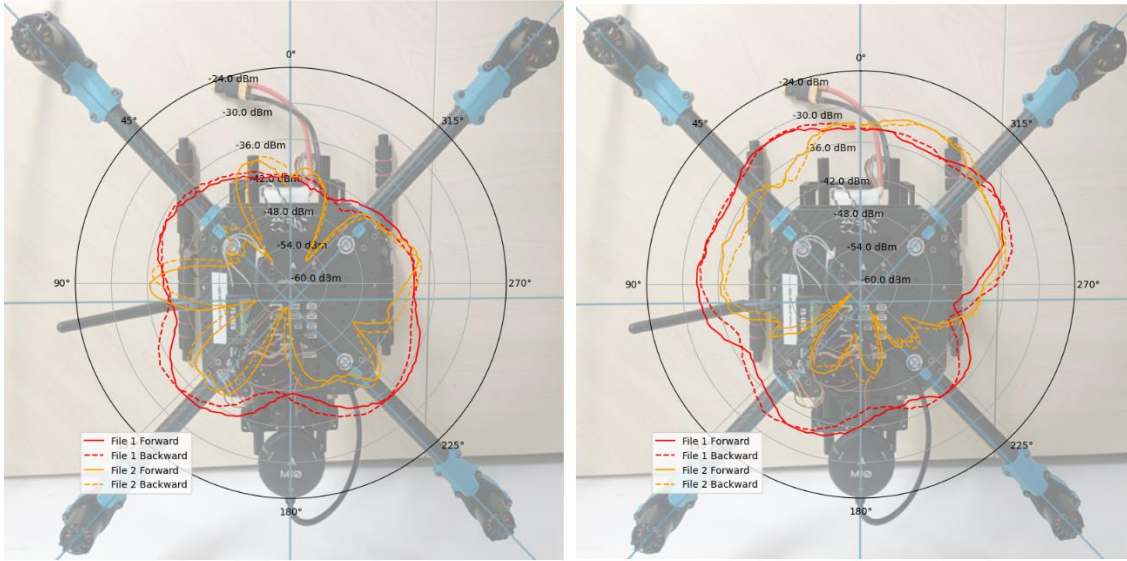
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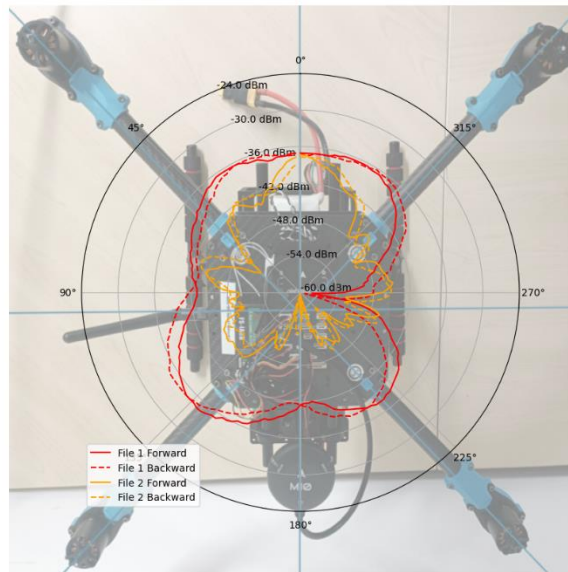
Appendix

A. Results



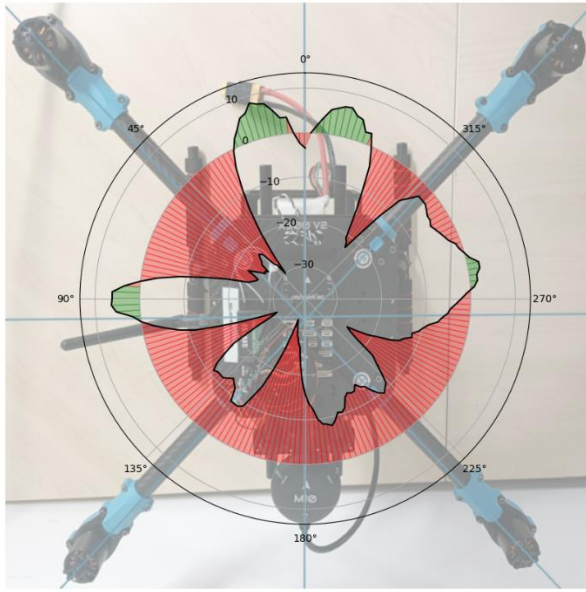
(a)

(b)

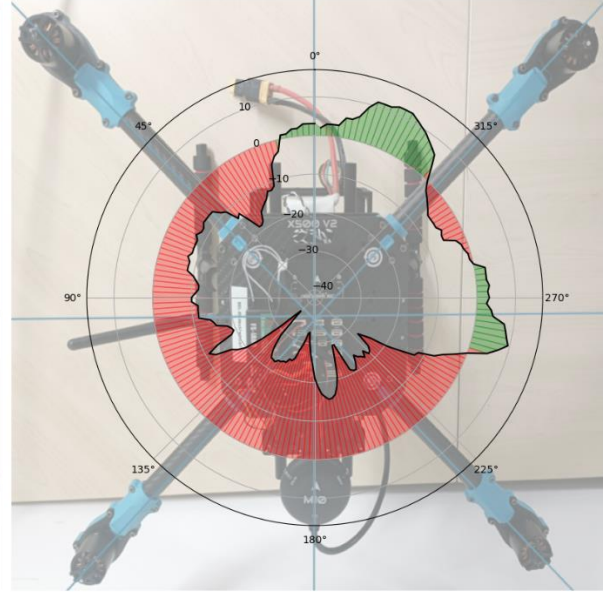


(c)

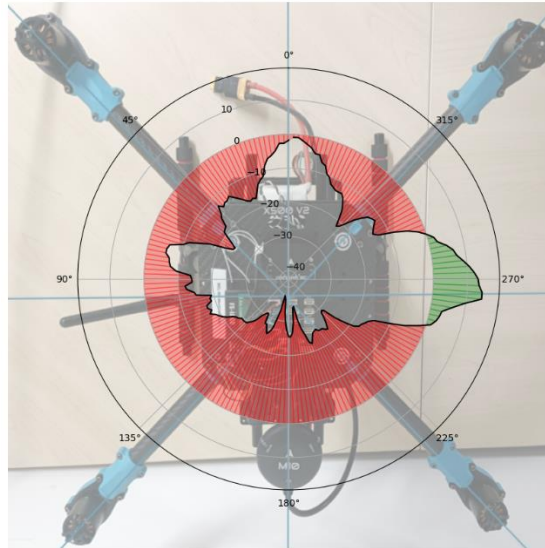
Figure A-1: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.455\text{GHz}$ and $Att = 13.03\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



(a)

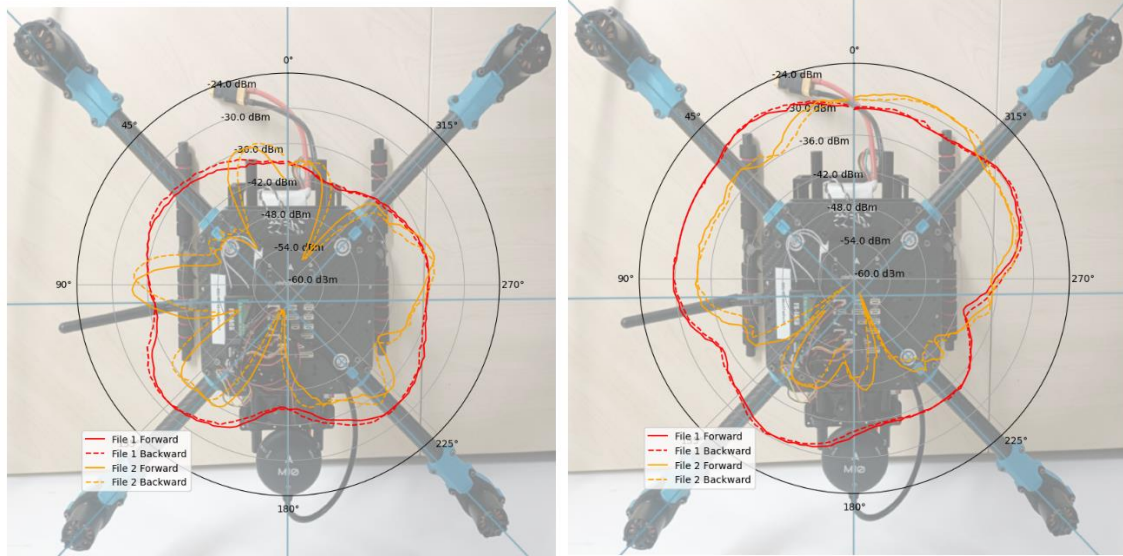


(b)



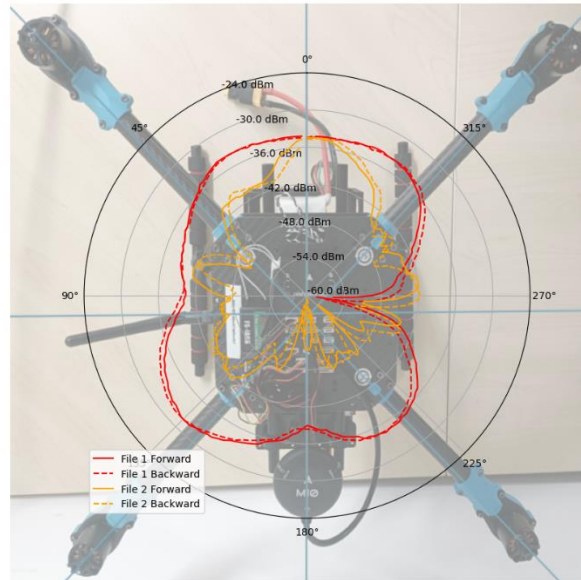
(c)

Figure A-2: Shielding percentage SP for $f=3.455\text{GHz}$ and $Att = 13.03 \text{ dBm}$ for the x-axis (a), y-axis (b) and z-axis (c) The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.



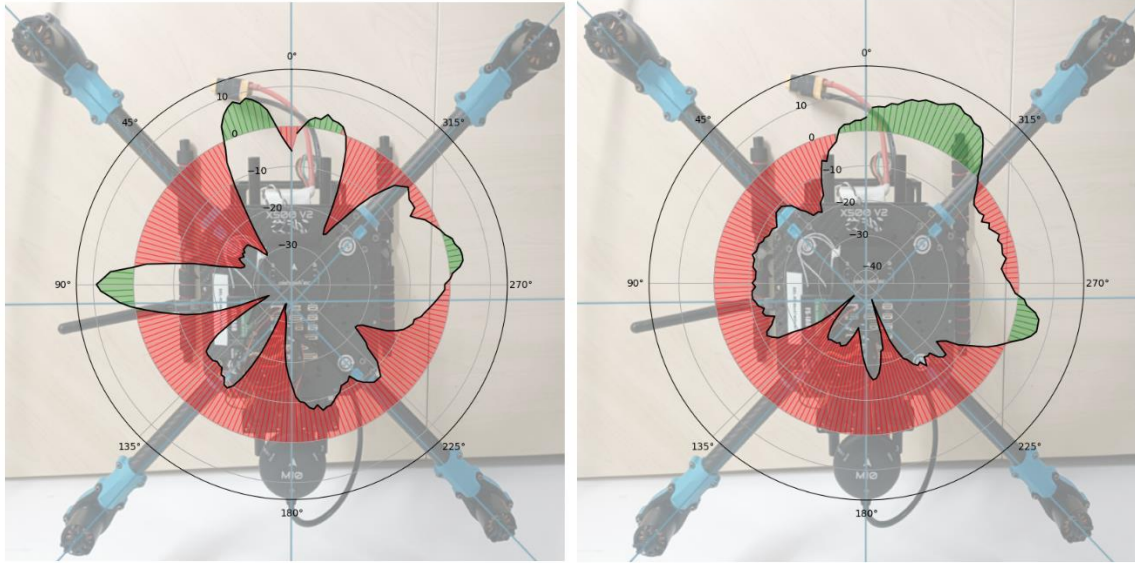
(a)

(b)



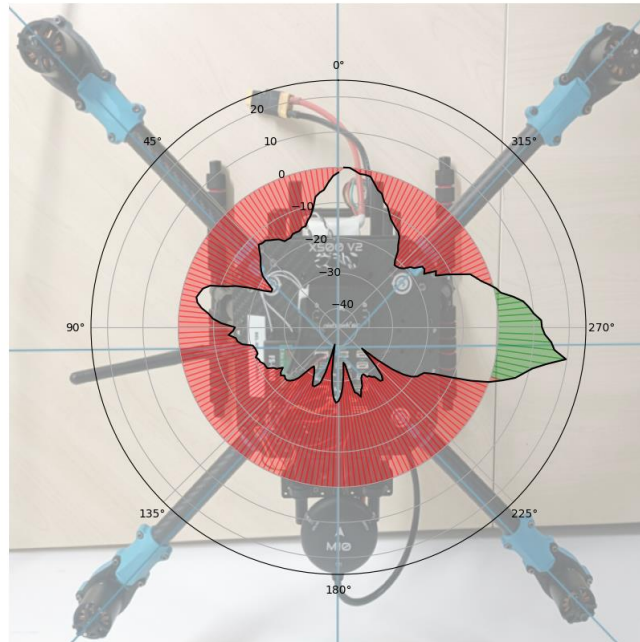
(c)

Figure A-3: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.455\text{GHz}$ and $A_{tt}=15.81\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



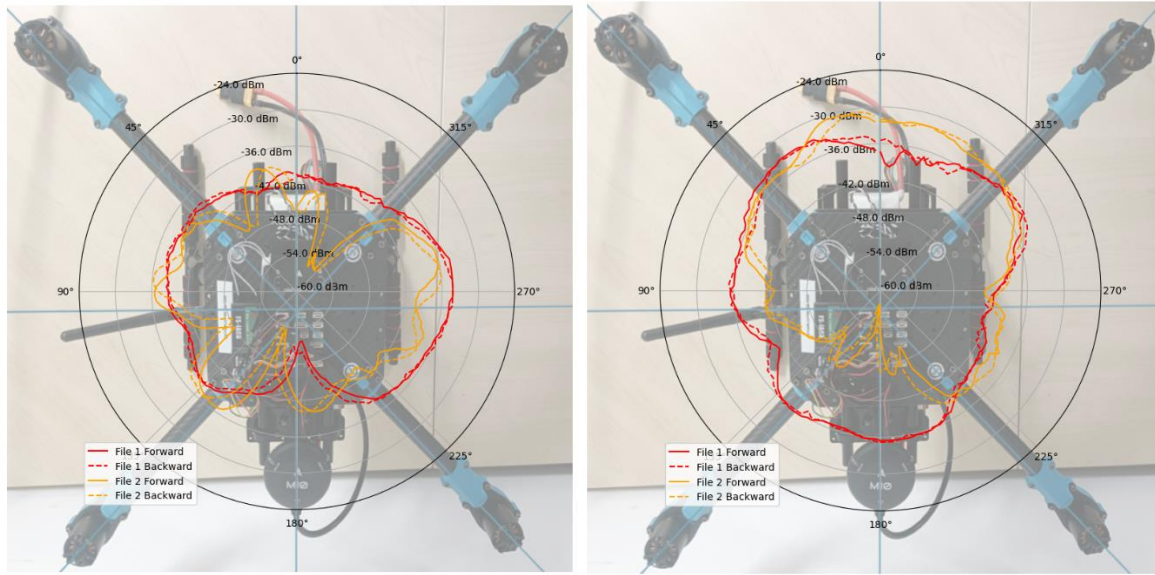
(a)

(b)



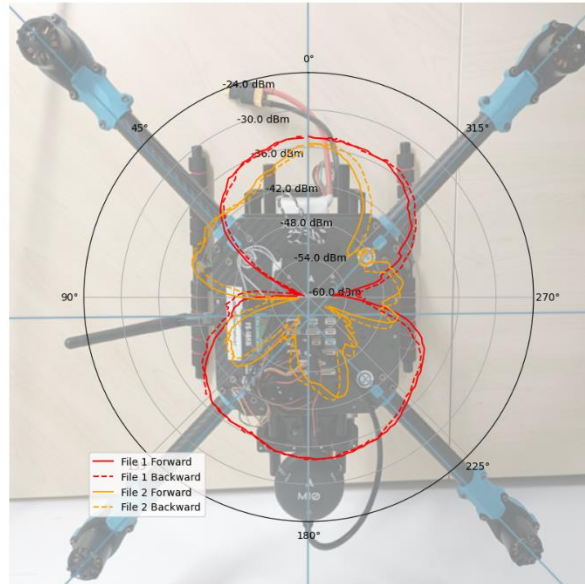
(c)

Figure A-4: Shielding percentage SP for $f=3.455\text{GHz}$ and $Att = 15.81 \text{ dBm}$ for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.



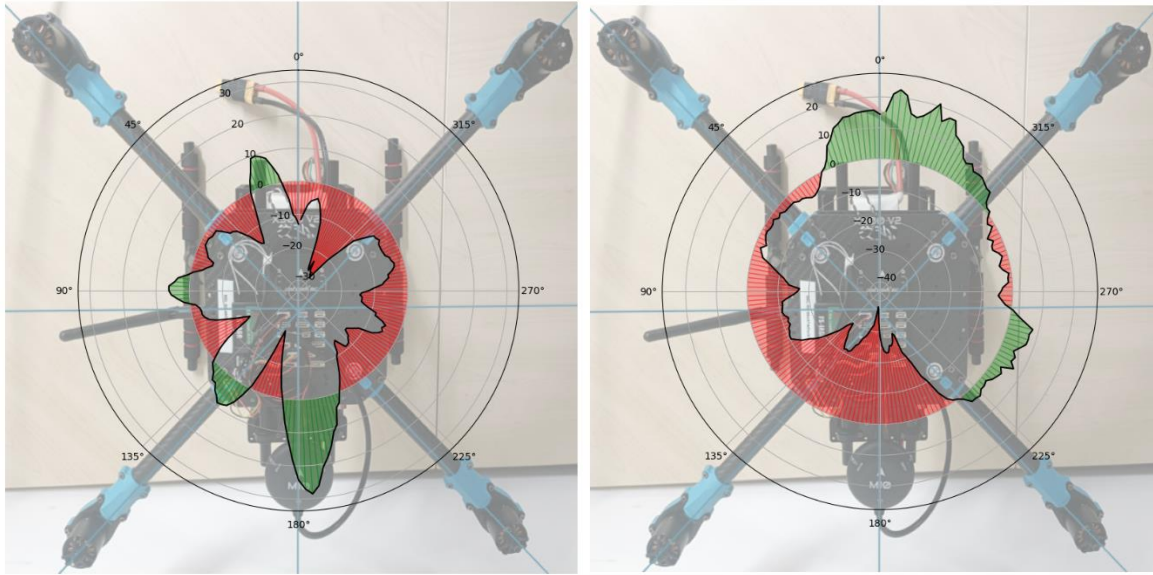
(a)

(b)



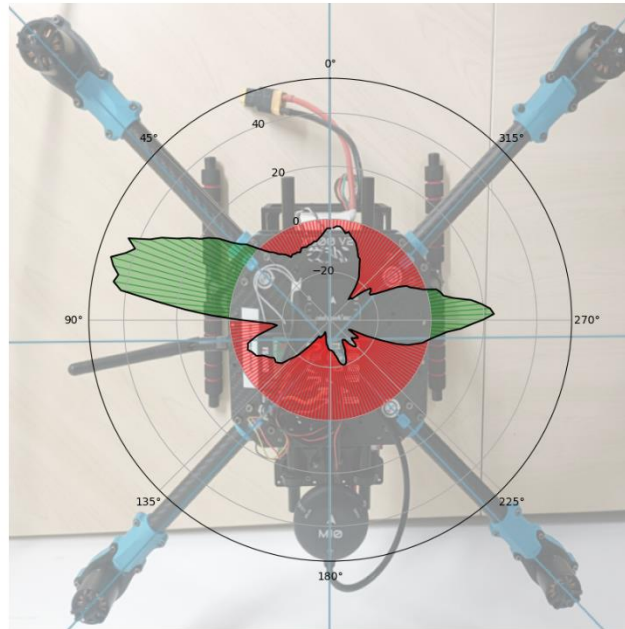
(c)

Figure A-5: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.530\text{GHz}$ and $Att = 13.20\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



(a)

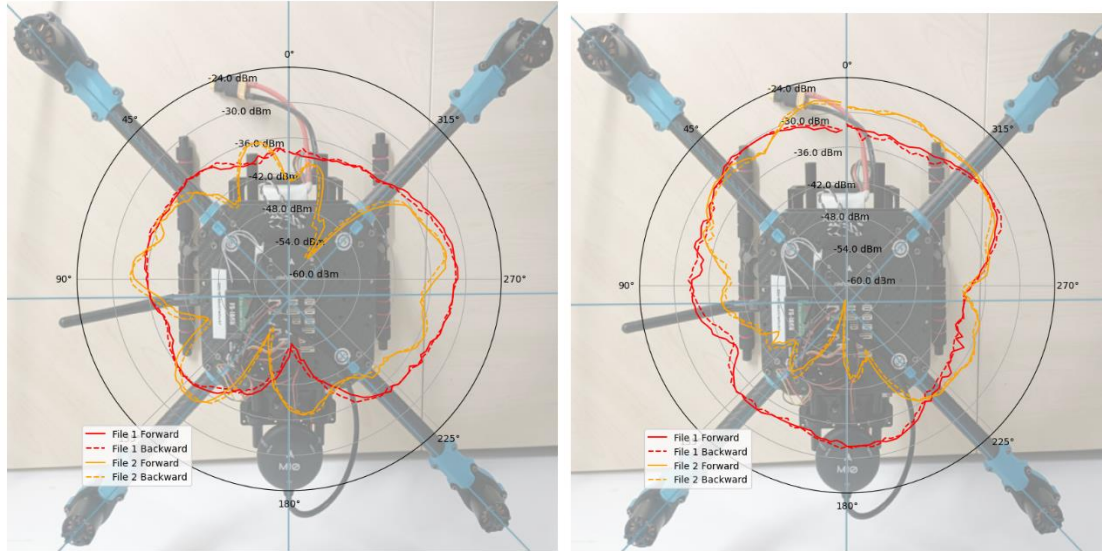
(b)



(c)

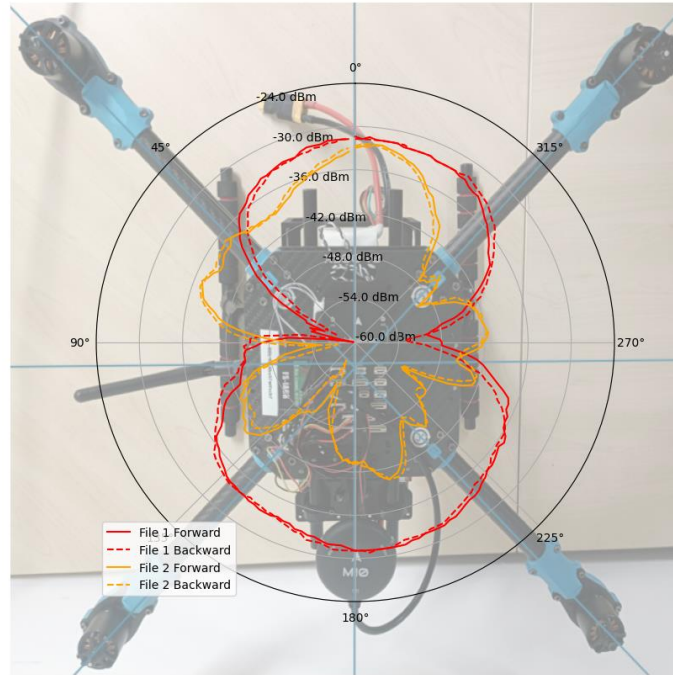
Figure A-6: Shielding percentage SP for $f=3.530\text{GHz}$ and $Att = 13.20 \text{ dBm}$ for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.

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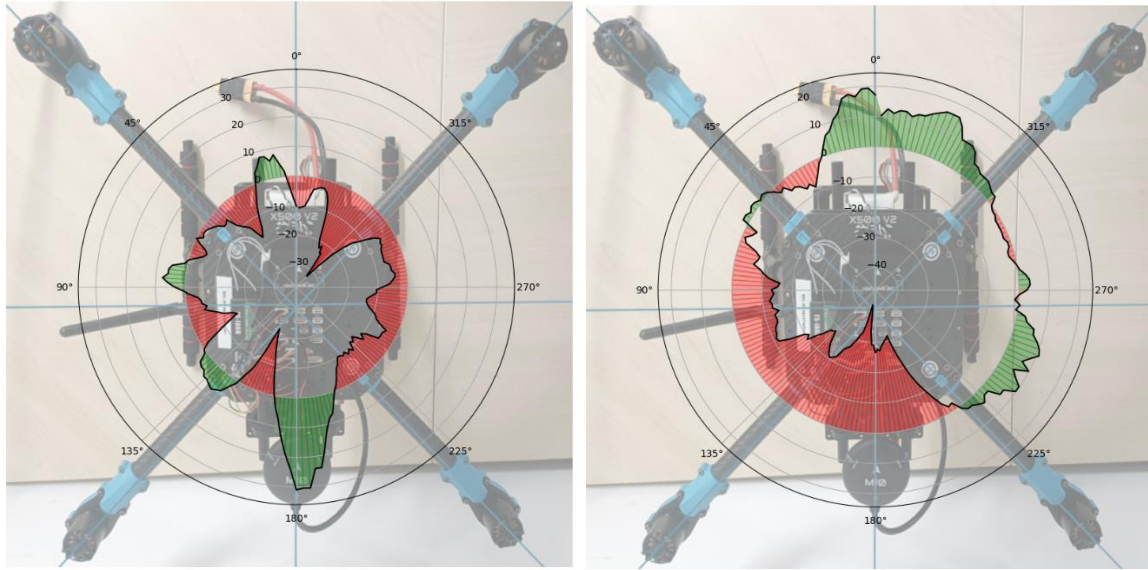
(a)

(b)



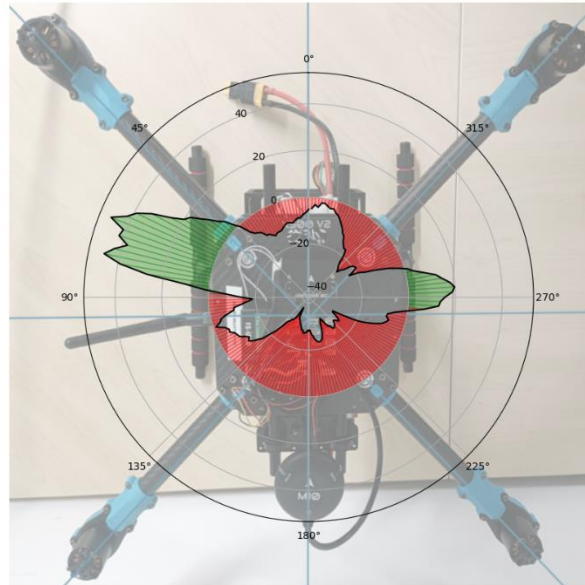
(c)

Figure A-7: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.530\text{GHz}$ and $Att=16.14\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



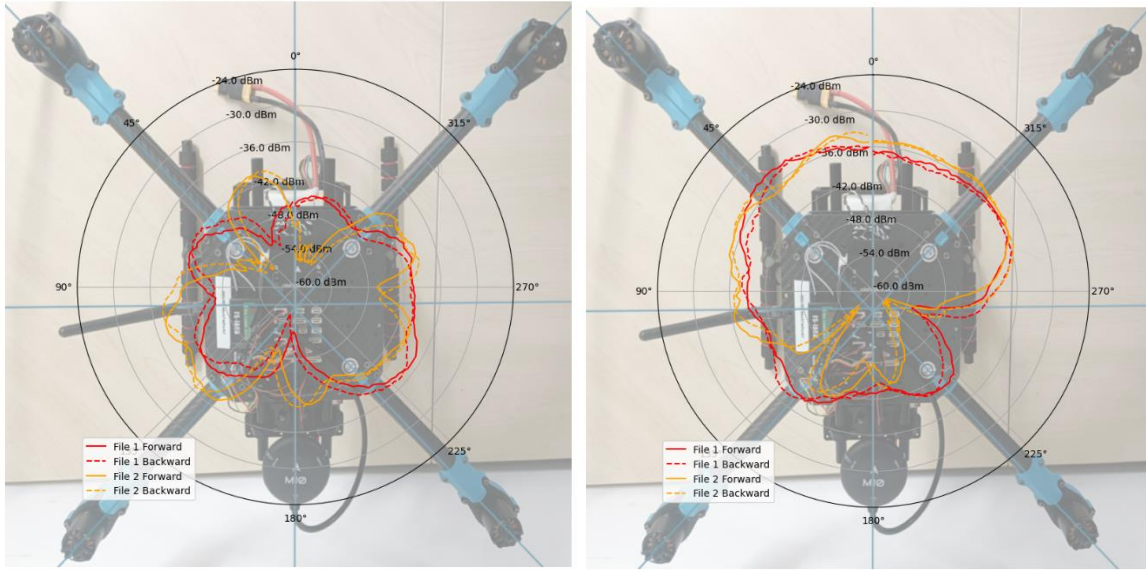
(a)

(b)



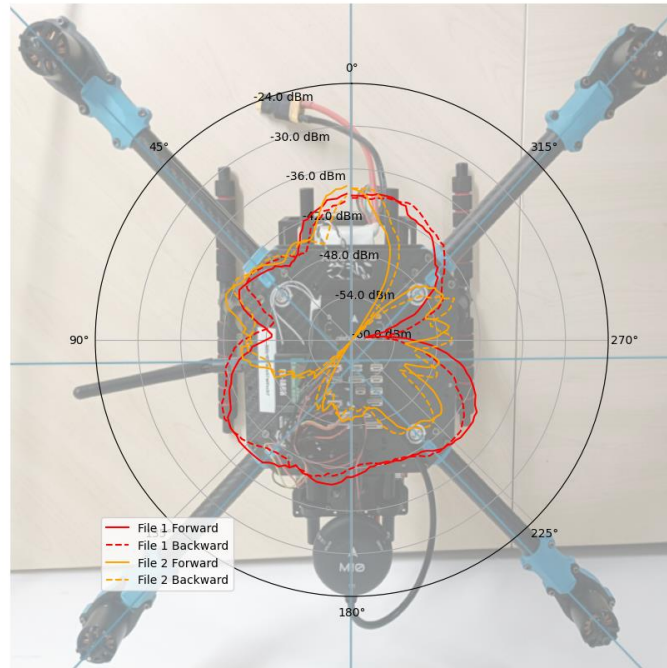
(c)

Figure A-8: Shielding percentage SP for $f=3.530$ GHz and $Att = 16.14$ dBm for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.



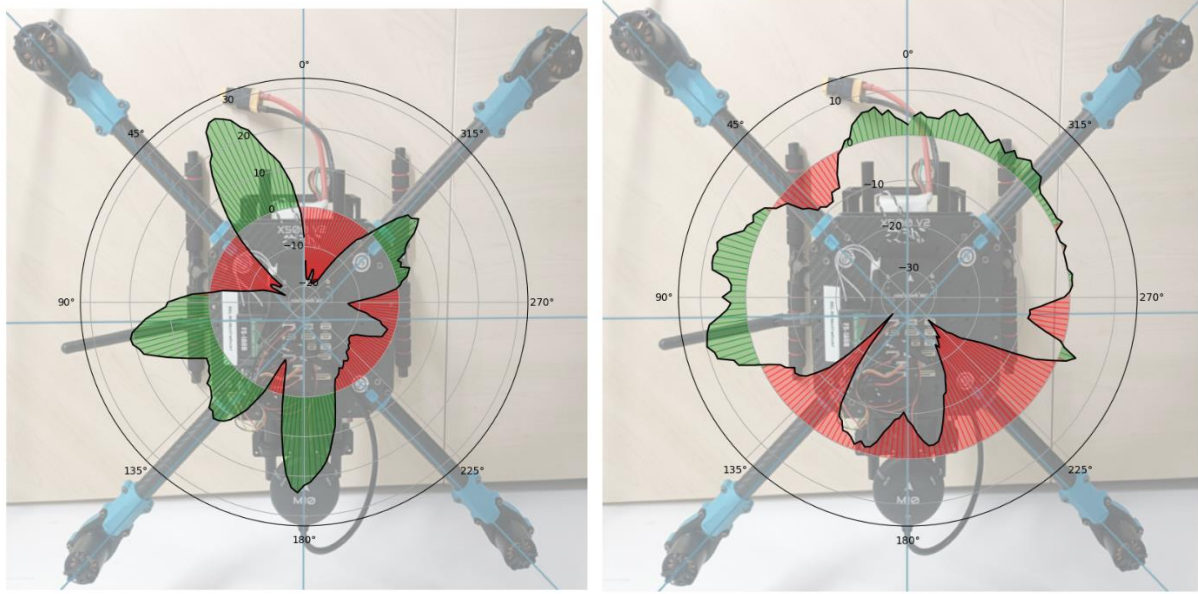
(a)

(b)



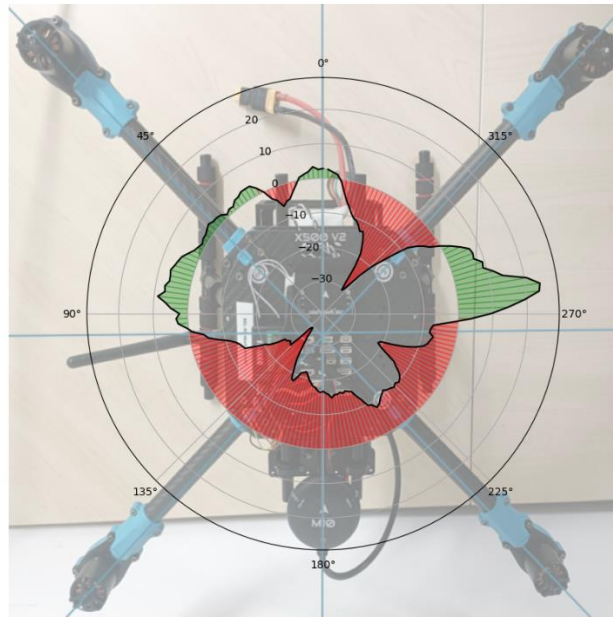
(c)

Figure A-9: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.650\text{GHz}$ and $Att=13.28\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



(a)

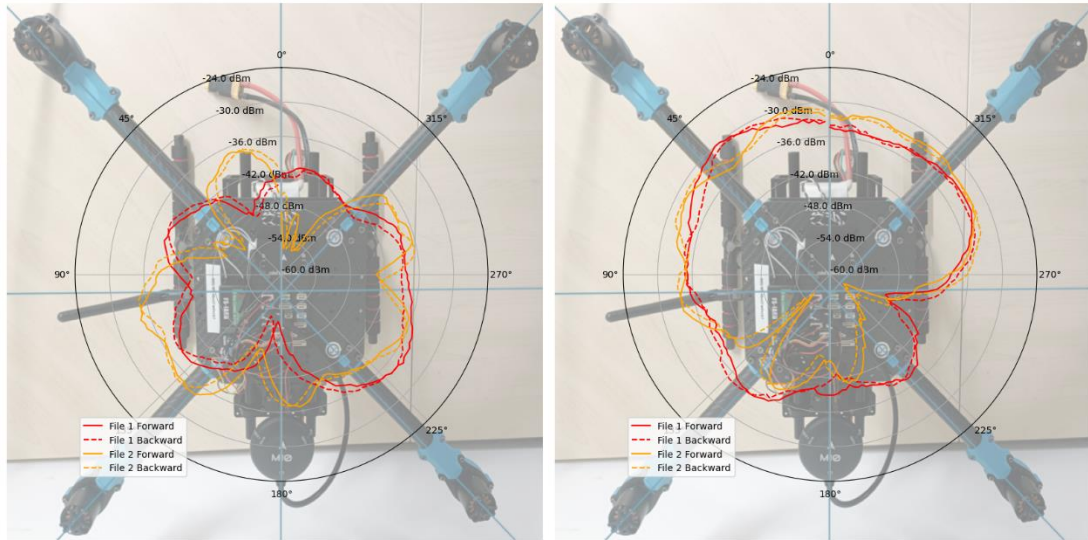
(b)



(c)

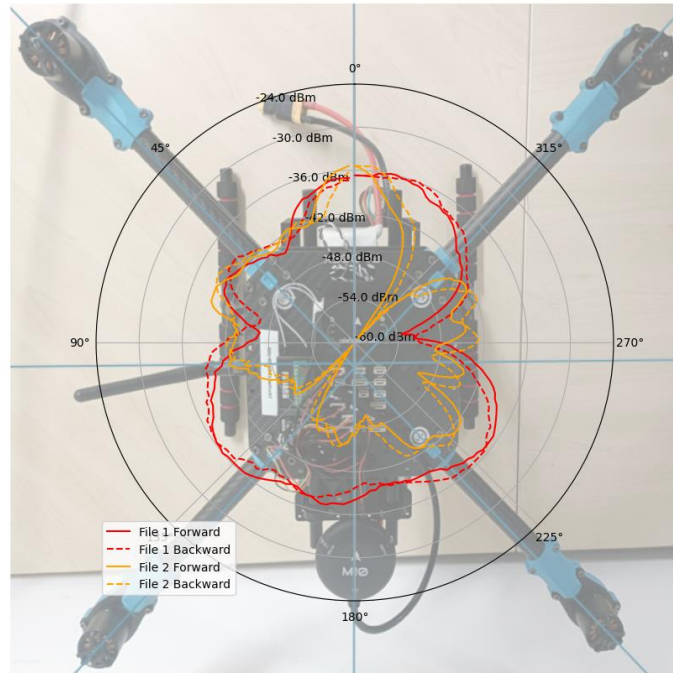
Figure A-10: Shielding percentage SP for $f=3.650$ GHz and $Att = 13.28$ dBm for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.

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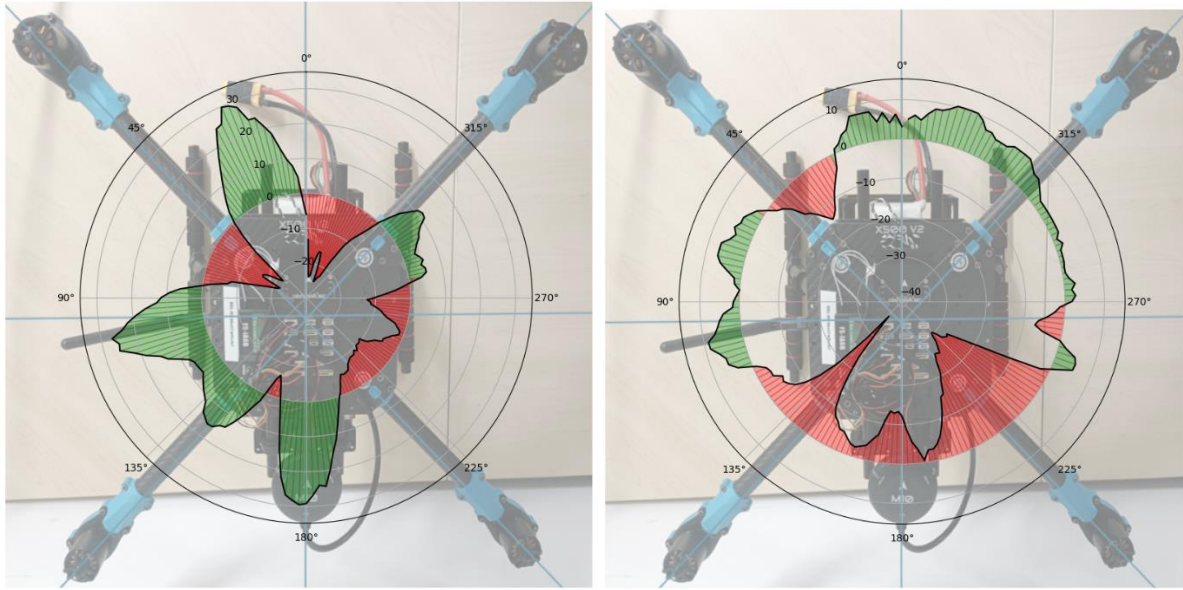
(a)

(b)



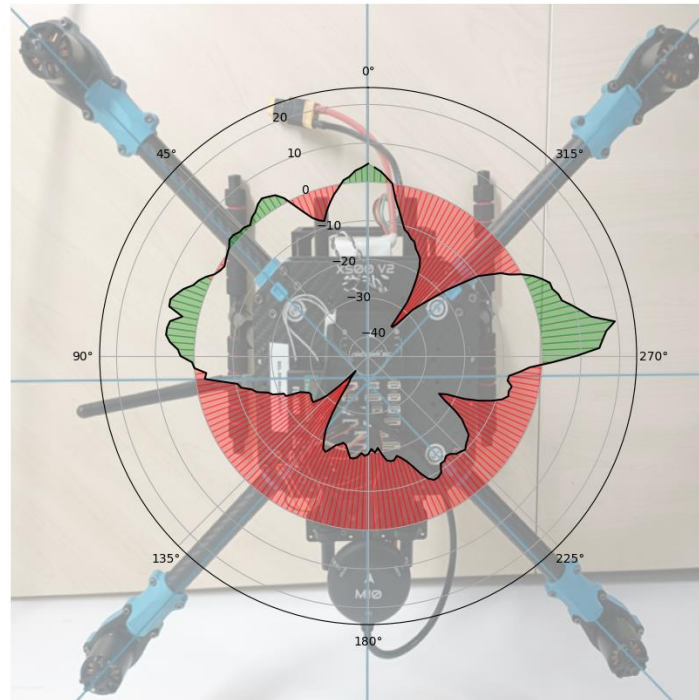
(c)

Figure A-11: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.650\text{GHz}$ and $A_{\text{t}}=16.14\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)



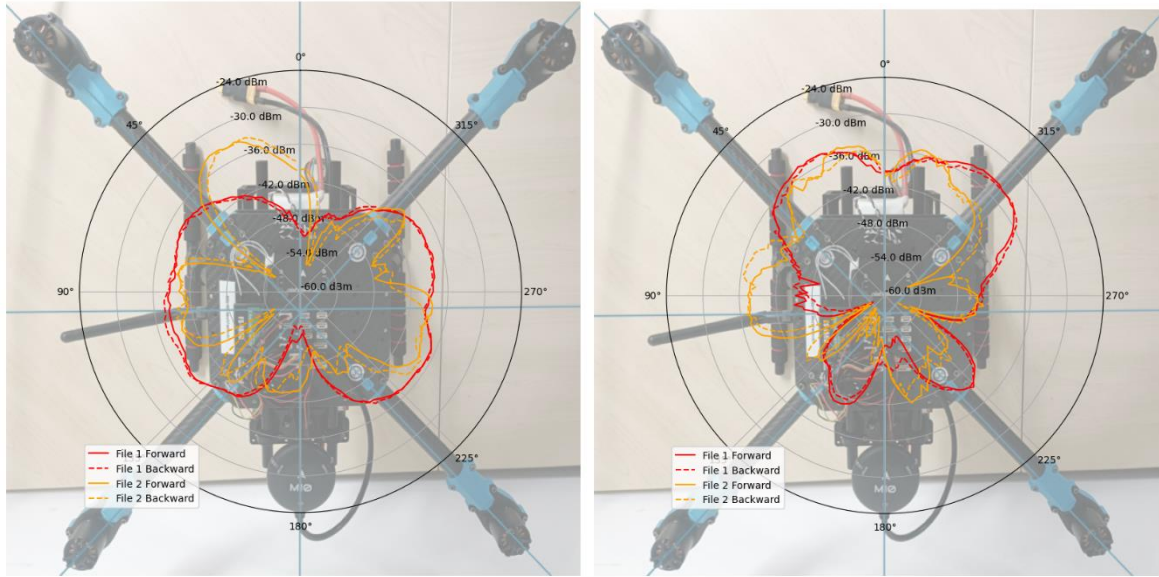
(a)

(b)



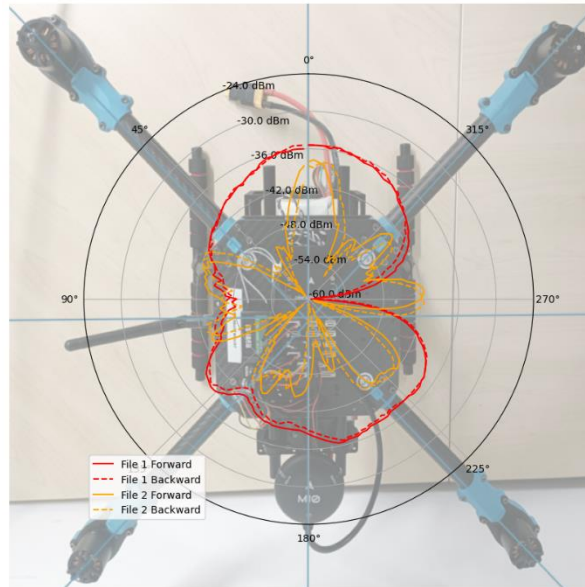
(c)

Figure A-12: Shielding percentage SP for $f=3.650$ GHz and $Att = 16.14$ dBm for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.



(a)

(b)



(c)

Figure A-13: Received power P_r in [dBm] from the drone with the sensor and the sensor alone captured on the x-axis with $f=3.750\text{GHz}$ and $Att = 16.18\text{ dBm}$ (a) for the y-axis (b) for the z-axis (c)

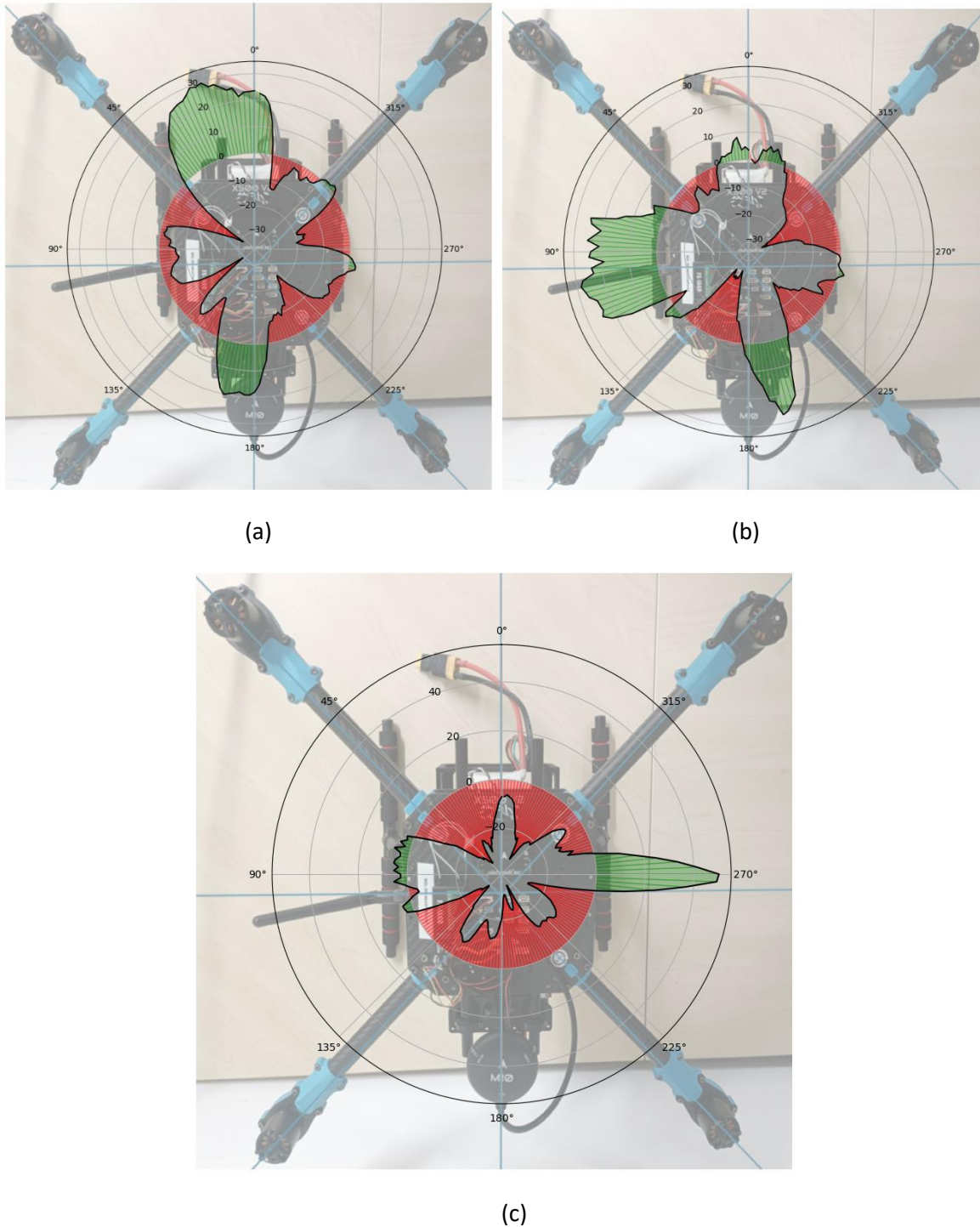


Figure A-14: Shielding percentage SP for $f=3.750$ GHz and $Att = 16.18$ dBm for the x-axis (a), y-axis (b) and z-axis (c). The red coloured area represents the area where $SP_{axis} \leq 0\%$. In this area the drone effectively attenuates the incident power signal. The green coloured area represents the area where $SP_{axis} \geq 0\%$. In this area the drone effectively amplifies the incident power signal.

B. Python code

All Python code used for data-processing, visualization and the autonomous drone flight can be found in Github Repository: <https://github.ugent.be/jonaerme/Autonomous-quadcopter-RF-EMF-monitoring.git>.