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ULTRA-WIDEBAND ANTENNA DESIGN AND PLACEMENT IN EMBEDDED INDOOR POSITIONING SYSTEMS

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Vertti Eronen

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ABSTRACT

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Keywords: Ultra-wideband (UWB), IEEE 802.15.4z, wireless positioning, indoor positioning system, two-way ranging, time-difference of arrival, angle of arrival.

Ultra-wideband (UWB) is an emerging radio technology that is commonly used for high precision wireless positioning of objects and people. UWB positioning systems often involve a set of "anchors" at fixed locations that are used to track the location of a mobile target device. This thesis investigates the mechanical dimensions and placement of the antennas of UWB positioning anchors.

A literature review is performed to establish the principles of common UWB positioning techniques and what is their relationship with the placement and dimensions of UWB antennas. The local regulations on UWB positioning are also investigated. An UWB development kit with positioning capability is used to test the effect of commonly encountered materials near its antennas, the goal is to simulate the device being embedded in furniture.

Three common positioning techniques were identified and each was found to have their own unique requirements for antenna placement. The antenna dimensions were found to be largely defined by the operating frequency. Local regulations were found to place limits on the available solutions in some circumstances. All tested materials were found to have a significant impact on the development kit's performance in certain conditions.

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Ultra-wideband (UWB) on hiljattain suosioon noussut radioteknologia, jota käytetään usein ihmisten ja esineiden korkean tarkkuuden langattomaan sisätilapaikannukseen. Yleensä UWB -paikannusjärjestelmät koostuvat kiinteästi asennetuista “ankkureista”, joita käytetään liikkuvan kohdelaitteen sijainnin seuraamiseen. Tässä diplomityössä tutkitaan UWB -paikannusankkureiden antennien mittasuhteita ja niiden sijoittelua.

Yleisten UWB -paikannusmetodien toiminta ja niiden vaikutus antennien mittasuhteisiin ja sijoitteluun selvitetään kirjallisuuskatsauksen keinoin. Myös paikallista UWB -paikannusjärjestelmiä koskevaa lainsäädäntöä tutkitaan. Paikannukseen soveltuvaa UWB -kehitysalustaa käytetään sen antennien läheisyydessä olevien materiaalien vaikutuksen kokeelliseen mittaamiseen. Mittausten tavoite on simuloida laitteen sulauttamista sisustukseen.

Kolme tyypillistä paikannusmetodia tunnistettiin, joista jokaisella todettiin olevan omat vaatimuksensa antennien sijoitteluun liittyen. Antennien mittasuhteiden todettiin määräytyvän pitkälti käyttötaajuuden mukaan. Paikallisen lainsäädännön todettiin rajoittavan mahdollisia toteutustapoja. Kaikkien testatuiden materiaalien havaittiin vaikuttavan merkittävästi kehitysalustan suorituskykyyn tietyissä olosuhteissa.

SYMBOLS AND ABBREVIATIONS

Symbols

B_{frac}	Fractional bandwidth	[Hz]
c	Speed of light	$[3.0 \times 10^8 \frac{m}{s}]$
C_{offs}	Clock offset compensation	[-]
d	Distance	[m]
D_{prop}	Propagation distance	[m]
f_0	Channel center frequency	[Hz]
f_{H}	High -10 dB cutoff frequency	[Hz]
f_{L}	Low -10 dB cutoff frequency	[Hz]
h	Height	[m]
L	Length	[m]
T_{prop}	Propagation time	[s]
T_{reply}	Reply time	[s]
T_{round}	Round-trip time	[s]
W	Width	[m]
ΔL	Length extension term	[-]
$\Delta\varphi$	Phase-difference	[°]
ε_{r}	Dielectric constant	[-]
ε_{eff}	Effective dielectric constant	[-]
θ	Angle of arrival	[°]
λ	Wavelength	[m]

Abbreviations

AOA Angle Of Arrival

BPM Burst Position Modulation

BPSK Binary Phase-shift Keying

DAA Detect And Avoid

DS-TWR Double-sided Two-way Ranging

DUT Device Under Test

EIRP Equivalent Isotropically Radiated Power

ERDEV Enhanced Ranging-capable Device

ETSI European Telecommunications Standards Institute

EU European Union

FCC Federal Communication Commission

GDOP Geometric Dilution Of Precision

HRP High-rate Pulse Repetition Frequency

IEEE Institute Of Electrical And Electronics Engineers

IoT Internet Of Things

IPS Indoor Positioning System

LDC Low Duty-cycle

LOS Line-of-sight

LRP Low-rate Pulse Repetition Frequency

MAC Medium Access Control

MPA Microstrip Patch Antenna

NLOS Non-line-of-sight

OOK On-off Keying

PBFSK Pulsed Binary Frequency Shift Keying

PCB Printed Circuit Board

PDOA Phase-difference Of Arrival

PHY Physical Layer

PPM Pulse-position Modulation

PRF Pulse Repetition Frequency

PSD Power Spectral Density

RDEV Ranging-capable Device

RSS Received Signal Strength

RTLS Real-time Locating System

RTT Round-trip Time

SS-TWR Single-sided Two-way Ranging

STS Scrabled Timestamp Sequence

TDOA Time-difference Of Arrival

TOF Time Of Flight

TWR Two-way Ranging

UWB Ultra-wideband

VSWR Voltage Standing Wave Ratio

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1 INTRODUCTION

Precise real-time positioning of devices is vital to guarantee the seamless operation of location based IoT applications. Traditional indoor positioning systems, commonly based on Wi-Fi or Bluetooth, require relatively high power and complex infrastructure to operate. In recent years ultra-wideband (UWB) has risen to prevalence in the sphere of indoor positioning technologies, supposedly offering very low power and accurate real time positioning capabilities compared to traditional methods. This thesis explores the spatial properties and placement guidelines of UWB antennas in small-scale embedded positioning applications.

1.1 Background

UWB is summarized by (Matin, 2010), as a radio technology that uses very short, low power pulses of radio signals over very wide bands of over 500 MHz in the 3.1 GHz to 10.6 GHz range to transmit data over short distances. Research on UWB has been ongoing since the 1960's with the main interest in radar applications for military purposes. UWB was first introduced to the commercial market when the Federal Communication Commission (FCC) approved the unlicensed use of UWB in 2002. UWB still remained a rather niche technology for the early 2000's, with the main research interests still in radar applications in the industrial, mining and medical fields.

By the end of the 2010's the focus of commercial UWB development had shifted to wireless positioning, ranging and short range data transmission to accommodate the needs of location dependent IoT applications, such as indoor navigation systems. The first properly mainstream implementation of UWB in consumer electronics came with Apple's U1 UWB -chip included in the 2019 iPhone 11 (Pluemer, 2022). Since then many other high-end smartphones and -watches have implemented UWB in some form. A clear sign of the rising interest in UWB is the emergence of organizations dedicated to development and standardization of UWB, like the FiRa Consortium specifically dedicated to UWB positioning and ranging, and UWB Alliance which is aims to further standardize UWB globally (FiRa Consortium, 2023)(UWB Alliance, 2023).

What makes UWB particularly attractive for industrial and consumer IoT are its low power consumption, resistance to interference and its separation from legacy wireless technologies in terms of both its operating frequency range and transmission power (Matin, 2010). As IoT applications become ever more common, the 2.4 GHz and 5 GHz bands used primarily by Wi-Fi and Bluetooth are becoming increasingly strained which can result in connectivity issues in high traffic environments. Because UWB operates on different frequency bands and much lower transmission power it isn't affected by high Wi-Fi or Bluetooth traffic.

1.2 Objectives

The main goal of this thesis is to identify the main factors that affect the placement of antennas in an UWB positioning system, as well as their mechanical dimensions. The purpose of this document is serve as reference material to aid in the design of UWB positioning systems. These kind of devices can come in many different shapes and sizes, the emphasis of this thesis is on small-scale devices that can be seamlessly embedded into furniture. To achieve the goals if this thesis, a basic overview of the operating principles of UWB with an emphasis on positioning applications is required as well as some way of determining how much do different materials in the immediate vicinity of an UWB antenna affect is performance. Some secondary objectives were also chosen, since they were either indirectly related to the main objective or were otherwise deemed interesting.

The main objective and the research questions needed to fulfill it are summarized below:

- What are the placement guidelines and mechanical dimensions of antennas in an UWB positioning system?

To answer this question the following things need to be established:

- What is UWB and how is it used for positioning and ranging?
- What are the factors that dictate UWB antenna placement and dimensions?
- How is UWB positioning affected by the materials surrounding the antenna(s)?

Secondary objectives:

- What are the desired electrical properties of UWB antennas?
- What are the regulatory limits on UWB frequency range and radiation power in the EU?
- Security, performance under interference, data rates.

1.3 Methods and delimitations

The first half of this thesis aims to establish the theoretical basis for modern UWB positioning, this will be done through literature research. The goal is to obtain a sufficient understanding of the common UWB positioning techniques that currently used in such systems and what is their role in determining the dimensions and placement of UWB antennas. In the second half an UWB development kit is used to experimentally determine what kind of an effect do the materials surrounding the antennas have on the device's performance. The delimitations for this thesis are summarized below:

- Wireless positioning systems typically consist of a certain number of static ”anchors” with known locations in space that are used to track moving target devices. This thesis is about the anchors, not the devices that are tracked by such systems.
- Novel solutions will mostly be excluded, the emphasis on the currently standardized positioning techniques that are actually used in commercial products.
- The software and firmware will play a part in the measurements, however the details of their implementation are excluded.
- Any wireless communication is subject to standards and regulations that often vary between countries. The regulations on UWB positioning present in the European Union (EU) will be the defining authority when applicable. A full regulatory review is beyond the scope of this thesis.

1.4 Structure of the thesis

This thesis is divided into 5 chapters. Chapter 2 contains a general overview of UWB positioning technology and the regional regulations on UWB positioning systems. Chapter 3 focuses on the spatial properties and placement guidelines of antennas in UWB positioning systems. Chapter 4 describes practical measurements that were performed to support the literature research. The results are gathered and analyzed in chapter 5 and the chapter 6 presents the conclusion and ideas for future research.

2 UWB POSITIONING AND RANGING

This chapter is a general overview of UWB positioning systems, with the purpose of providing the necessary context for the next chapter, where the spatial design guidelines for UWB antennas are discussed. The objective of this chapter is to establish a general definition of UWB and basic principles of UWB positioning. Most currently available UWB devices with positioning capability operate based on the Institute of Electrical and Electronics Engineers (IEEE) standard 802.15.4(z), so the positioning techniques defined by this standard are the main takeaway of this chapter. Regional regulations on radio spectrum access and emission limits also play a role in the antenna design process, so the EU regulations on UWB positioning systems are briefly covered here. These regulations, standardized by European Telecommunications Standards Institute (ETSI), dictate the allowed frequency band(s) and power limits for UWB positioning devices and how they are allowed to operate in different environments. Data rates, security and reliability of UWB were also deemed to be a point of interest.

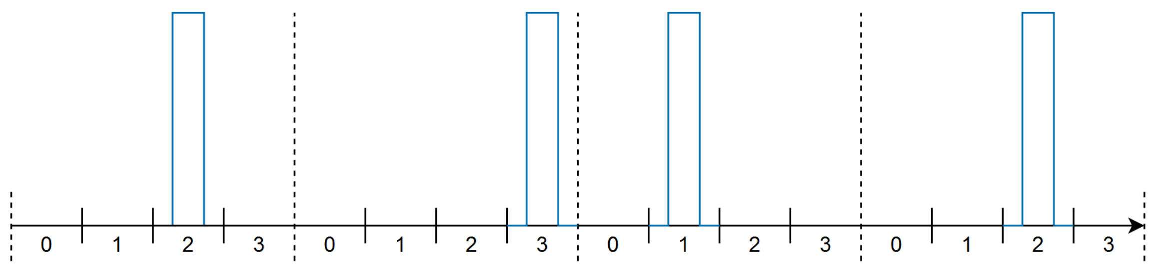


Figure 1: UWB at its simplest form uses short sequences of distinct pulses (blue) to transmit information, an example of PPM is presented in this figure.

According to (Matin, 2010), conventional wireless communication technologies typically transmit information by modulating a sinusoidal carrier wave, that is continuously transmitted on relatively narrow channels of the radio spectrum. Information is transmitted by varying the frequency, amplitude or phase of the carrier wave, usually some combination of the three is used. UWB on the other hand, instead of a encoding data onto a continuous carrier wave, communicates by transmitting very short wideband pulses at certain time intervals. Information is transmitted by sending and receiving short bursts of multiple distinct pulses. The duration of these bursts is typically between tens of picoseconds to a few nanoseconds, so a great deal of time domain accuracy is required for the participating devices. A simple example of how this can be done is to alter the timing of each individual pulse within the time frame of the burst, this is called pulse-position modulation (PPM), which is illustrated in figure 1. The polarity and the amount of pulses, as well as other additional signal properties can be used for more complicated modulation schemes.

2.1 UWB definition & regulations

UWB devices operate on channels up to tens of times wider than WiFi and hundreds of times wider than Bluetooth with very low overall signal power. An intentional radiator that has a bandwidth greater than or equal to 500 MHz or a fractional bandwidth greater than or equal to 0.2 is considered to be an UWB transmitter (FCC, 2002).[1] Fractional bandwidth B_{f} is defined as:

$$B_{\mathrm{f}} = 2 \times \frac{f_{\mathrm{H}} - f_{\mathrm{L}}}{f_{\mathrm{H}} + f_{\mathrm{L}}}, \tag{2.1}$$

where f_{H} is the highest frequency point -10 dB below signal level and f_{L} is the lowest frequency point -10 dB below signal level.

Generally UWB devices operate within the range of 3.1 GHz to 10.6 GHz, their upper limit for equivalent isotropically radiated power (EIRP) is -41.3 dBm/MHz (ETSI, 2016). Some radar imaging applications exist in the so called “sub-GHz” band between roughly 250 MHz and 750 MHz (Matin, 2010). However, radar imaging doesn’t seem to have as much commercial interest behind them compared to positioning applications.

A 2019 report by ETSI documents the global regulatory status of UWB (ETSI, 2019a). When the FCC first approved the unlicensed use of UWB in the United States, it set the rules for the frequency range and radiation power levels for UWB devices. This original set of rules and guidelines from 2002 forms the basis for global UWB regulations today. Although the FCC regulations are technically exclusive to the United States, so much of the semiconductor industry is concentrated in the U.S. that UWB devices are almost guaranteed to adhere to FCC regulations at least. For the purposes of this thesis the local, arguably more stringent, rules within the EU are applied. Since the focus of this thesis is in the positioning and ranging applications of UWB, the ETSI -standard for UWB location tracking (ETSI EN 302 065-2 V2.1.1) will be used, the series which this standard is a part of covers the essential requirements of article 3.2 of the EU Directive 2014/53/EU (ETSI, 2016).[2] Additional information

[1]Some sources cite the fractional bandwidth limit as 0.25, this was the proposed definition in the FCC’s first report on UWB, the final definition was and still is 0.20 (FCC, 2002)(FCC, 2023).

[2]It may be possible for a positioning device to be classified under the generic use case of the: “*Harmonised Standard covering the essential requirements of article 3.2 of the Directive 2014/53/EU; Part 1: Requirements for Generic UWB applications*” (ETSI EN 302 065-1 V2.1.1).

on the global status of UWB regulations can be found in ETSI TR 103 181-3 V2.1.1: *"Short Range Devices (SRD) using Ultra Wide Band (UWB); Part 3: Worldwide UWB regulations between 3,1 and 10,6 GHz"* (ETSI, 2019a).

2.1.1 Positioning systems

When UWB is used for tracking the location of some target, the system typically consist of a certain number of fixed "anchors" with known locations, these anchors are then used to track a mobile target (commonly referred to as "tags") device of some sort. EU regulations and ETSI standards define how and where UWB location tracking systems are allowed to operate. All location tracking systems are allowed to receive signals on the full UWB band, limits apply mainly on transmitting. ETSI EN 302 065-2 V2.1.1 (ETSI, 2016) defines three different types of location tracking systems that each have their own permitted frequency ranges and radiation limits, with some additional requirements specific to certain applications:[3]

- **LT1 systems** operate between 6.0 GHz to 9.0 GHz, and are intended for general location tracking of people and objects. Typically LT1 systems consist of a fixed receiver infrastructure that is used only to receive signals emitted by mobile tracking tags. These systems can operate unlicensed, mobile applications are allowed indoors or outdoors, fixed systems are only allowed indoors.

- **LT2 systems** operate between 3.1 GHz to 4.8 GHz, and are intended for location tracking of people and objects as well as industrial applications at well-defined locations. Transmitters may be located indoors and outdoors and be fixed or mobile. These devices operate at fixed sites and are subject to registration and authorization.[4]

- **LAES systems** operate between 3.1 GHz to 4.8 GHz, and are intended for tracking emergency service personnel. These systems enhance the coordination and safety of such personnel and are typically deployed temporarily at the site of a fire or some other emergency. User organizations may be required to license their systems.

For an indoor positioning system the LT1 category seems the easiest choice as far as regulations are concerned, since LT2 systems are subject to registration and authorization and LAES is a special case for emergency services. These classifications of course aren't mutually exclusive, a device may operate in some or all of the standardized scenarios provided that it is properly configured for its target environment. From a regulatory standpoint the LT1 definition is straightforward when only operating in an indoor space. However, when approaching

[3]ETSI EN 302 065-2 V2.1.1 does not cover LT1 UWB transmitters that are operated on board a road or rail vehicle running on a public network or highway. Vehicular applications are covered by ETSI EN 302 065-3 V2.1.1

[4]Additional requirements apply for the radiation pattern of outdoor LT2 terminals, see clauses 4.3.2.3 and 4.6.1 of ETSI EN 302 065-2 V2.1.1 for more information.

the line between indoor and outdoor applications, implementing LT1 systems becomes more complicated. Outdoor UWB transmitters connected to fixed infrastructure are prohibited by EU Commission decision (EU) 2019/785 on the 6 GHz to 9 GHz range (European Commission, 2019). The decision in question defines indoor use as "inside buildings or places in which the shielding will typically provide the necessary attenuation to protect radio communication services against harmful interference". Generally an outdoor application could be considered as a device installed in an environment where it would be exposed to the weather, like mounted on the outside wall of a building (outdoor use isn't explicitly defined by the EU commission or ETSI). Fixed LT1 applications can still be used to receive signals in outdoor applications[5] and mobile LT1 devices are allowed both indoors and outdoors. Therefore it should be possible to build a fixed outdoor LT1 system only if the anchors operate on a receive only basis. This places some major restrictions on the possible positioning and ranging techniques as the communication can only happen one way: from the target device to the anchors.

2.1.2 Frequency and power limits

There are some regional differences on the band allocation on UWB devices, the upper limit of mean EIRP is almost universally -41.3 dBm/MHz, the peak EIRP limits are defined separately but are not commonly referenced in literature (ETSI, 2019a). The EIRP limits of LT1 systems are presented in figure 2 (ETSI, 2016). The upper limit of the LT1 operating frequency is either 8.5 GHz or 9 GHz depending on whether the device in question has implemented active interference mitigation in the form of detect and avoid (DAA), which is defined in (ETSI, 2014).

[5]Receiving isn't explicitly allowed but it is implied by decision (EU) 2019/785; the decision applies to UWB transmitters, not receivers.

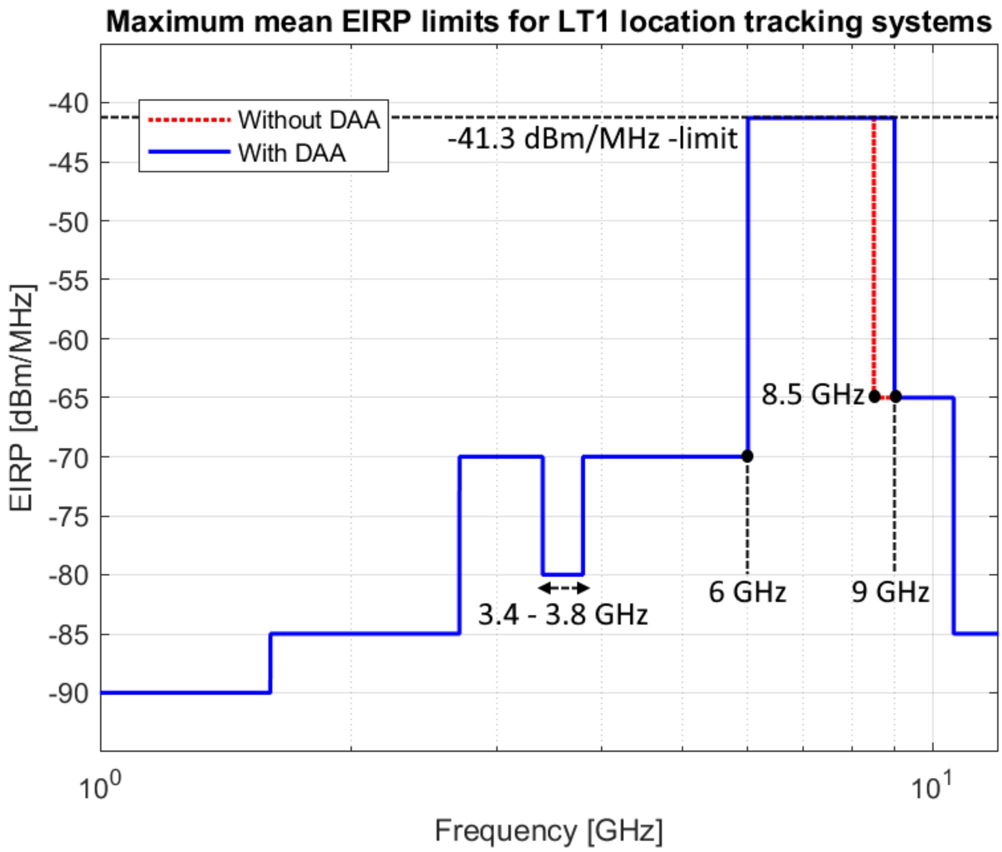


Figure 2: LT1 location tracking systems mean EIRP limits with and without DAA (ETSI, 2016).

According to (ETSI, 2014), DAA is an active interference mitigation technique where the UWB device detects the presence of other wireless devices like WiFi routers etc. and reduces its transmitting power or stops transmitting altogether to prevent interfering with nearby devices. The interfering device (UWB) should scan its intended channel before transmitting and if another device is detected, wait until the other signal disappears before transmitting. Alternatively the UWB device may switch to a different channel if one is available.[6] Another interesting thing in the graph is the -80 dBm/MHz dip between 3.4 and 3.8 GHz, this is the band where the first iterations of 5G communication systems were implemented on a global scale (GSMA, 2021).

[6]Additionally, LAES and LT2 are required to have low duty-cycle (LDC) -mitigation implemented, more information on this is available in (ETSI, 2014) and (ETSI, 2016)

2.1.3 Interference & reliability

The potential for UWB to interfere with narrowband (WiFi, Bluetooth, etc.) wireless devices has been a concern since the inception of the technology. The very low radiated power of UWB devices works to its advantage in this regard. Presented in figure 3, are the upper radiated power limits of UWB and other common wireless technologies (ETSI, 2019b)(ETSI, 2017). The wideband nature and low signal power of UWB makes it appear as slightly elevated levels of background noise from the perspective of traditional narrowband devices, as illustrated by figure 3. However, it is possible for UWB signals to significantly interfere with narrowband signals in cases where an UWB device is situated very close to a narrowband device or where the local concentration of active UWB nodes is high (Chiani and Giorgetti, 2009). Active interference mitigation techniques are therefore mandated by ETSI, for example.

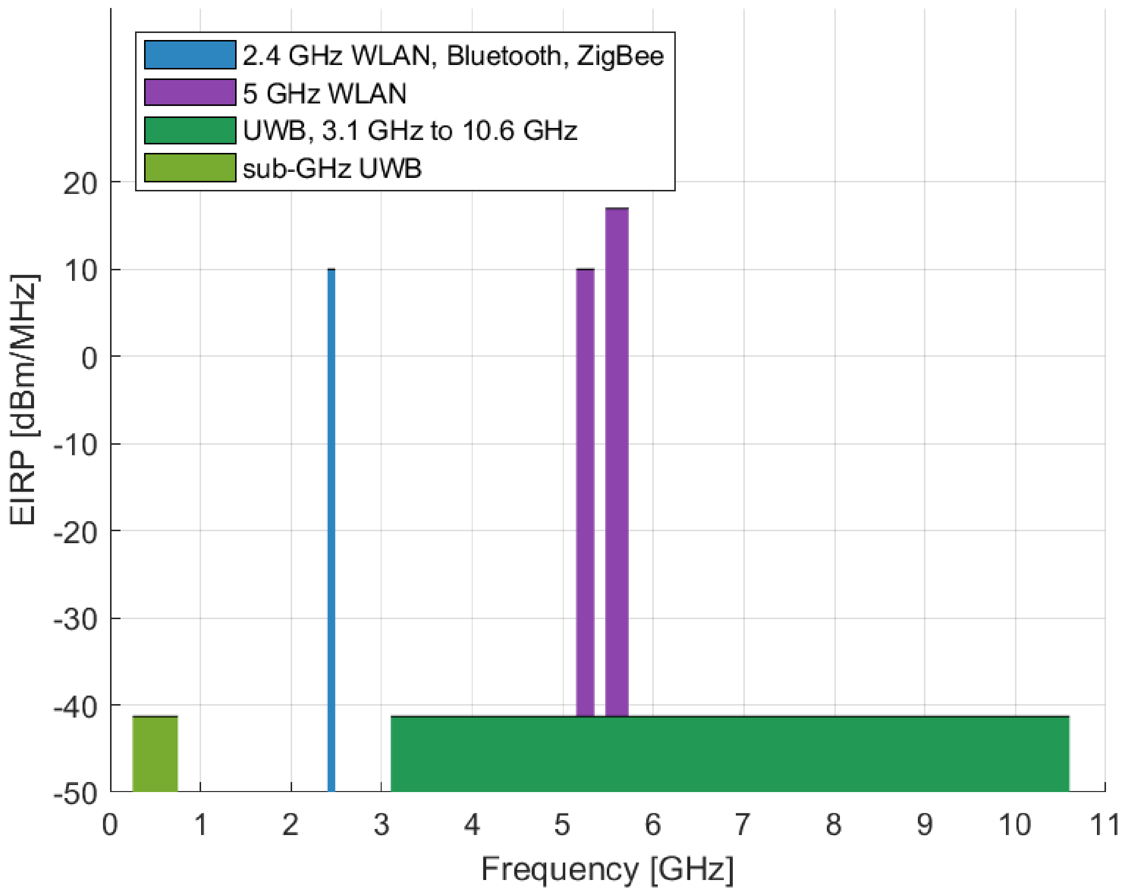


Figure 3: UWB emission levels compared to common wireless technologies (ETSI, 2019b)(ETSI, 2017).

The features of UWB signals significantly improve their resistance to multipath fading, an effect where reflections of the transmitted signal degrade the original signal (Matin, 2010).

The wideband nature of UWB reduces the probability of reflections at specific frequencies degrading the whole pulse to the point where it can't be decoded. Additionally when precise timestamps are involved in the communication, which is often the case when positioning is concerned, distinguishing the primary signal from reflections is easier. The signal with the shortest propagation path is going to arrive at the receiver first, assuming the speed of light is constant in the present medium.

2.2 IEEE 802.15.4z

The IEEE standard 802.15.4z[7] (IEEE, 2020b in references) is widely considered to be the foundation of modern UWB positioning applications (Henry, 2023). IEEE 802.15.4z is an amendment for an earlier IEEE standard: 802.15.4[8] (IEEE, 2020a in references). To make the narrative easier to follow, 802.15.4z is henceforth referred to as "Amendment 1" and 802.15.4 simply by its number. The 802.15.4 standard defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for UWB. Amendment 1 provides additional specifications for the UWB PHYs and most importantly: adds enhancements for UWB ranging and positioning. The different UWB PHYs are the most interesting specifications for the purposes of antenna design as they are directly related to the physical dimensions of the antenna. Amendment 1 and 802.15.4 define two PHYs for UWB: low-rate pulse repetition frequency (LRP) PHY and high-rate pulse repetition frequency (HRP) PHY, the pulse repetition frequency (PRF) refers to the number of pulses the transmitter in question emits within a certain time frame. The properties of the HRP- and LRP PHYs that are pertinent to UWB antenna design and location tracking are covered in the following sections. Security and data rates were also deemed to be a point of interest.

At the core of Amendment 1 are its enhancements to ranging and positioning. A device that supports those enhancements is referred to as an enhanced ranging-capable device (ERDEV). Generally UWB ranging functionality is based on precise timestamps of received/transmitted signals. While those are somewhat briefly described in 802.15.4, Amendment 1 adds a lot more detail to the different ranging and positioning techniques. The principles of UWB positioning and ranging and the techniques used to achieve them are layed out in section 2.3. The standardization process is still a work in progress, the next amendment to 802.15.4 is already being prepared by the name of IEEE 802.15.4ab, which is planned to be completed by the end of 2025 (Henry, 2023).

Another interesting feature of the ranging enhancements of Amendment 1 is its improved security. ERDEVs use various techniques to verify the authenticity of signal timestamps. The

[7] "IEEE Standard for Low-Rate Wireless Networks–Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques" (IEEE, 2020b).

[8] "IEEE standard for low-rate wireless networks" (IEEE, 2020a).

precise positioning and ranging capabilities of UWB devices can be used to enhance security by implementing distance bounding protocols, which means that the participating devices must verifiably be within a certain distance of each other. A malicious actor could penetrate distance bounding protocols by manipulating the timestamps of packets to appear to be within the distance bounding limit. HRP ERDEVs use a technique called scrabled timestamp sequence (STS) and LRP ERDEVs use challenge-response authenticated ranging to prevent such relay attacks, see sections 15.2.9 and 6.9.8 of Amendment 1 for more information on the security features.

2.2.1 HRP PHY

In Amendment 1 the HRP PHY is divided into three independent bands of operation: the sub-gigahertz band with a single channel at 499.2 MHz, the low band with four channels from 3494.4 MHz to 4492.8 MHz and the high band which has eleven channels from 6489.6 MHz to 9984.0 MHz. A list of HRP channels, their respective bands and whether they are required for compliance with the standard is presented in table 1. To be considered Amendment 1 -compliant a device must support at least one mandatory channel on its band(s) of operation: channel 0 for sub-GHz, channel 3 for low band and channel 9 for high band, these are marked with an asterisk in the table.

Table 1: HRP PHY channel bands, channel numbers, their center frequencies and bandwidths. Mandatory channels for each band are marked with an asterisk (IEEE, 2020a).

Band	Channel number	Center frequency [MHz]	Bandwidth [MHz]
Sub-GHz	0*	499.2	499.2
Low band	1	3494.4	499.2
	2	3993.6	499.2
	3*	4492.8	499.2
	4	3993.6	1331.2
High band	5	6489.6	499.2
	6	6988.8	499.2
	7	6489.6	1081.6
	8	7488.0	499.2
	9*	7987.2	499.2
	10	8486.4	499.2
	11	7987.2	1331.2
	12	8985.6	499.2
	13	9484.8	499.2
	14	9984.0	499.2
	15	9484.8	1354.97

The majority of the UWB market seems to be focused on smartphones and applications related to them, like wearable electronics and smart home devices (Zanella, 2022). As was mentioned in the introduction of this thesis, the first major consumer application of UWB was Apple's U1 -chip, which is based on the HRP PHY (Coppens et al., 2022). This set the precedent for using HRP PHY, and since the market is so heavily focused on smartphones it makes sense for the most popular UWB chips overall to use the HRP PHY for compatibility reasons, if nothing else. Since Amendment 1, both HRP PHY and LRP PHY include ERDEV capabilities, but the HRP PHY provides considerably faster data rates, albeit with a higher power consumption, which makes it more versatile and therefore more attractive to developers. The mean PRF of the HRP PHY is 249.6 MHz at its highest, which allows it to transfer data faster than its slower counterpart. The HRP PHY uses a modulation scheme called BPM-BPSK, short for burst position modulation (BPM) and binary phase-shift keying (BPSK), which allows it to send 2 bits of data per symbol (IEEE, 2020a). The Amendment 1 HRP PHY can provide data rates of up to 31.2 Mb/s .[9]

2.2.2 LRP PHY

The Amendment 1 version of LRP PHY operates on ten channels within the band of 6489.6 MHz to 9945.6 MHz. The LRP PHY provides data rates of up to 10 Mb/s depending on the mode of operation. As of Amendment 1, LRP PHY supports six modes of operation with an emphasis on either sensitivity[10], data rate or power consumption, see table 2. Originally the LRP PHY band consisted of three channels, Amendment 1 added seven channels, bringing the total to ten, six of which have ERDEV functionality. The 802.15.4 version of LRP PHY used either on-off keying (OOK) or pulse-position modulation (PPM), Amendment 1 added pulsed binary frequency shift keying (PBFSK) to the supported modulation schemes, which is primarily used for ERDEVs.

[9]UWB devices could theoretically reach data rates of up to 480 Mb/s and beyond, vastly faster than the currently standardized speeds (Matin, 2010).

[10]Minimum received signal power that the receiver can accurately decode.

Table 2: A summary LRP PHY modes of operation and their features (IEEE, 2020b).

Modes of operation			
Mode	**Data rate**	**PRF [MHz]**	**Features**
Base mode	1 Mb/s	1.0	The baseline
Extended mode	250 kb/s	1.0	Better sensitivity, lower data rate
Long range mode	31.25 kb/s	2.0	Best sensitivity, lowest data rate
Dual-frequency mode	1 Mb/s to 4 Mb/s	1.0 to 4.0	Lower power consumption
Extended dual-frequency mode	250 kb/s to 1 Mb/s	1.0 to 4.0	Better sensitivity, lower data rate
Dual-frequency mode with EPC	3 Mb/s to 10 Mb/s	1.0 or 2.0	Highest data rates

A summary of LRP PHY channels is presented in table 3. Note that the channel bandwidth in this context is the bandwidth between the 0 dBr limits of LRP PHY channelized power spectral density (PSD) mask, which is defined in section 18.7.3 of Amendment 1. For some unclear reason the channel bandwidths for the LRP PHY and HRP PHY are presented differently in Amendment 1, even though they are defined in the same standard. The HRP PHY channels are defined simply by their nominal bandwidths while the LRP PHY channels are defined by their radiation limits. Another strange feature of the standard is that the reference level of the radiated power in the channelized PSD mask of the LRP PHY isn't clearly stated in the standard. The exact 0 dBr reference level is defined in section 15.4 of Amendment 1, but it's very convoluted. However the standard does state that "The maximum allowable output PSD shall be in accordance with practices specified by the appropriate regulatory bodies", which should be enough in this context.

Table 3: LRP PHY channelized PSD mask and 0 dBr bandwidths, channels 4 to 9 are ERDEV capable (IEEE, 2020b).

Channel band number	Center frequency [MHz]	0 dBr bandwidth [MHz]	ERDEV
0	6489.6	1406.08	No
1	6988.8	2146.56	No
2	7987.2	1730.56	No
3	8486.4	2146.56	No
4	6681.6	848.6	Yes
5	7334.4	848.6	Yes
6	7987.2	848.6	Yes
7	8640	848.6	Yes
8	9292.8	848.6	Yes
9	9945.6	848.6	Yes

The LRP PHY provides a low power alternative to the HRP PHY with lower overall data rates. For battery powered applications where the volume of data transmissions is low and power efficiency is critical the LRP PHY is clearly the more attractive option. As mentioned before however, when looking at the current state of the UWB market the arguably more versatile HRP PHY is the more commonly implemented solution.

2.3 Positioning with IEEE 802.15.4z

As mentioned before, the basic concept of wireless positioning is to use a certain number of individual anchors with known locations in space to exchange transmissions between mobile tag, and use the measured properties of such transmissions to determine the relative location of the target. The basic measurements that these systems use to compute the location/range of the target are: received signal strength (RSS), time of flight (TOF) and angle of arrival (AOA), or some combination of the three (Bensky, 2008). RSS based positioning is achieved by measuring the power level of received signals and using that information to determine its origin, RSS is not commonly used in UWB positioning systems. Most modern UWB positioning systems use different TOF measurements to determine the distance or location of objects. Amendment 1 specifies three basic measurement protocols, all of which are based on measuring the TOF of signals between participating devices (IEEE, 2020b). TOF is the time it takes for a signal propagate from one device to another (Bensky, 2008). The measurements are achieved by exchanging precise receive/send time-stamps, and can be used for simple ranging to full 3D positioning depending on the anchor configuration. The ranging and positioning measurements defined by Amendment 1, and how the AOA of a received signal can be derived from those measurements are covered in the following subsections.

2.3.1 Two-way ranging

Amendment 1 describes two round-trip time (RTT) based distance measurement techniques: single-sided two-way ranging (SS-TWR) and double-sided two-way ranging (DS-TWR) (IEEE, 2020b). The RTT is the time it for the initiating device to send a message to the target and receive a response back. When the time taken by the internal processes of the participant devices is known, the extra time can be subtracted from the RTT, resulting in the TOF between devices and with that the distance between them can be calculated.

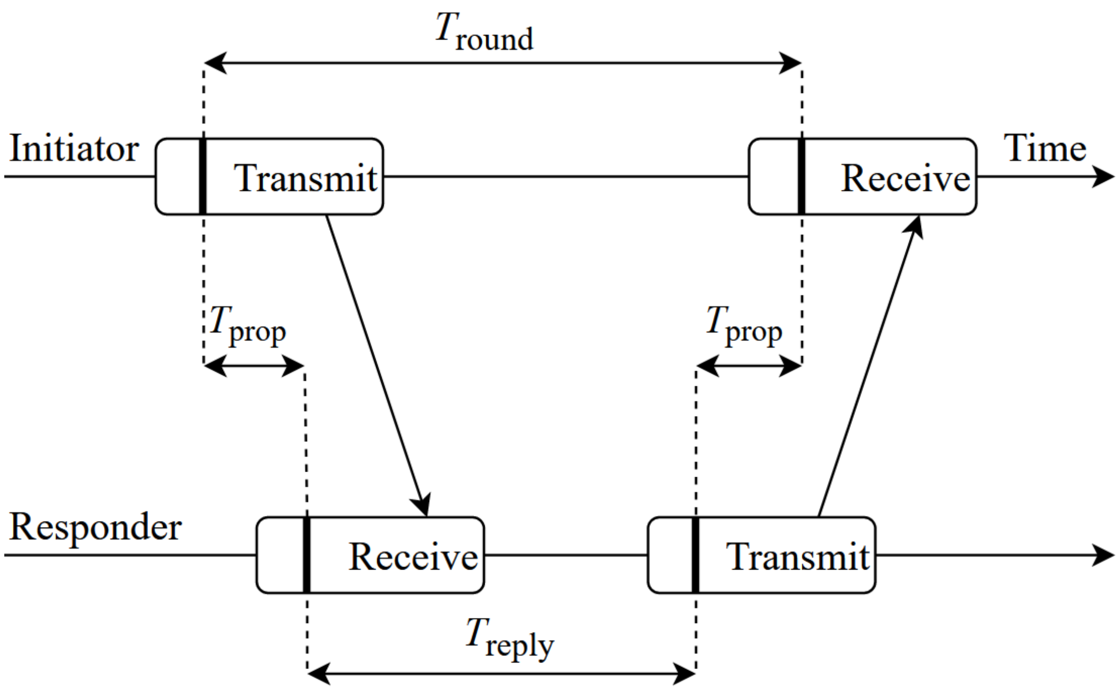


Figure 4: Visualization of the single-sided two-way ranging procedure, simplified from (IEEE, 2020b).

In SS-TWR an anchor device measures its distance to a target device (IEEE, 2020b). The operating principle of SS-TWR is presented in figure 4. The anchor device initiates the communication by sending a single message to the target, which the target processes and sends a response back. The times are measured relative to a marker in the message frame. The TOF can be calculated as follows:

$$T_{\text{prop}} = \frac{1}{2}(T_{\text{round}} - T_{\text{reply}}) = \frac{1}{2}(T_{\text{round}} - T_{\text{reply}} - (1 - C_{\text{offs}})), \tag{2.2}$$

where T_{prop}, T_{round} T_{reply} represent the TOF,the total measured RTT and the time the responder takes to receive, process and respond to the message sent by the initiator, respectively. Because the measurements are done by independent devices with their own clocks, there's most likely some offset between their respective clocks, which causes error to the measurements. C_{offs} is an optional term that compensates for the clock offset between participating devices, if the initiator is capable of clock offset correction.

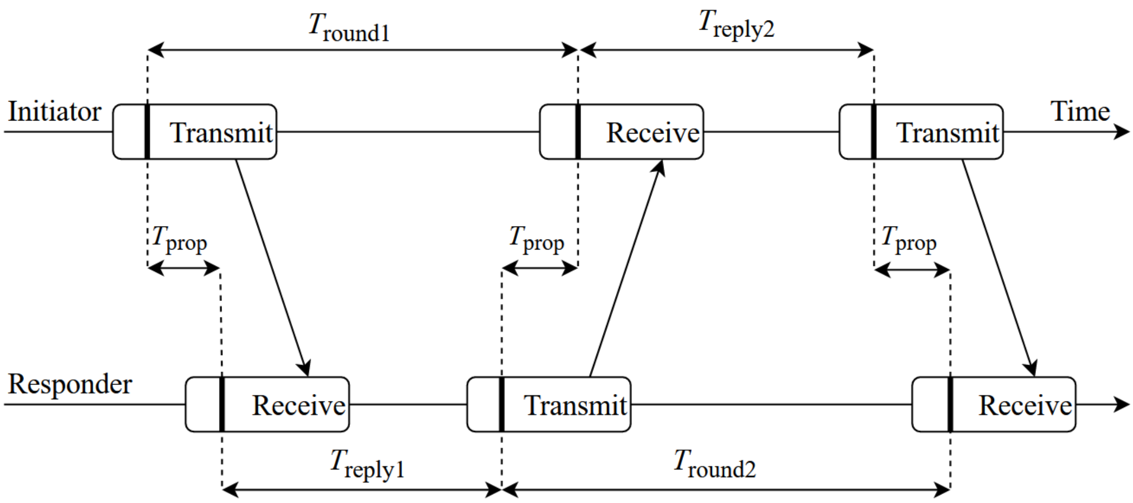


Figure 5: Visualization of the dual-sided two-way ranging procedure, simplified from (IEEE, 2020b).

DS-TWR is similar to SS-TWR but the ranging procedure is executed both ways, first from anchor to target and the other way around (IEEE, 2020b). In this way, both devices can access their relative distances, since the RTT is calculated both ways. DS-TWR is typically done with three messages. A visual representation of the DS-TWR measurement is presented in figure 5, the process begins similarly to SS-TWR, the difference comes when the target sends its response to the initiator. The target's response serves as the starting point for the RTT measurement from the target's side, after which the initiator sends a response to the target, completing the cycle and providing both devices with the RTT. The TOF of the DS-TWR measurement can be calculated as follows:

$$T_{\text{prop}} = \frac{T_{\text{round1}} \times T_{\text{round2}} - T_{\text{reply1}} \times T_{\text{reply2}}}{T_{\text{round1}} + T_{\text{round2}} + T_{\text{reply1}} + T_{\text{reply2}}}, \tag{2.3}$$

where T_{prop}, T_{round} T_{reply} represent the TOF,the total measured RTT and the reply time from responder to initiator and vice versa. (IEEE, 2020b).

The distance resulting from the TOF for both methods is given by:

$$D_{\text{prop}} = T_{\text{prop}} \times c, \tag{2.4}$$

where $c = 3.0 \times 10^8 \frac{m}{s}$. At its simplest form two-way ranging (TWR) can be used to measure the distance between two devices furthermore, one can extend the ranging capability of TWR to full 3D positioning by introducing multiple tracking anchors. Figure 6 contains a conceptual image of TWR positioning with three anchors performing their own TWR measurements.

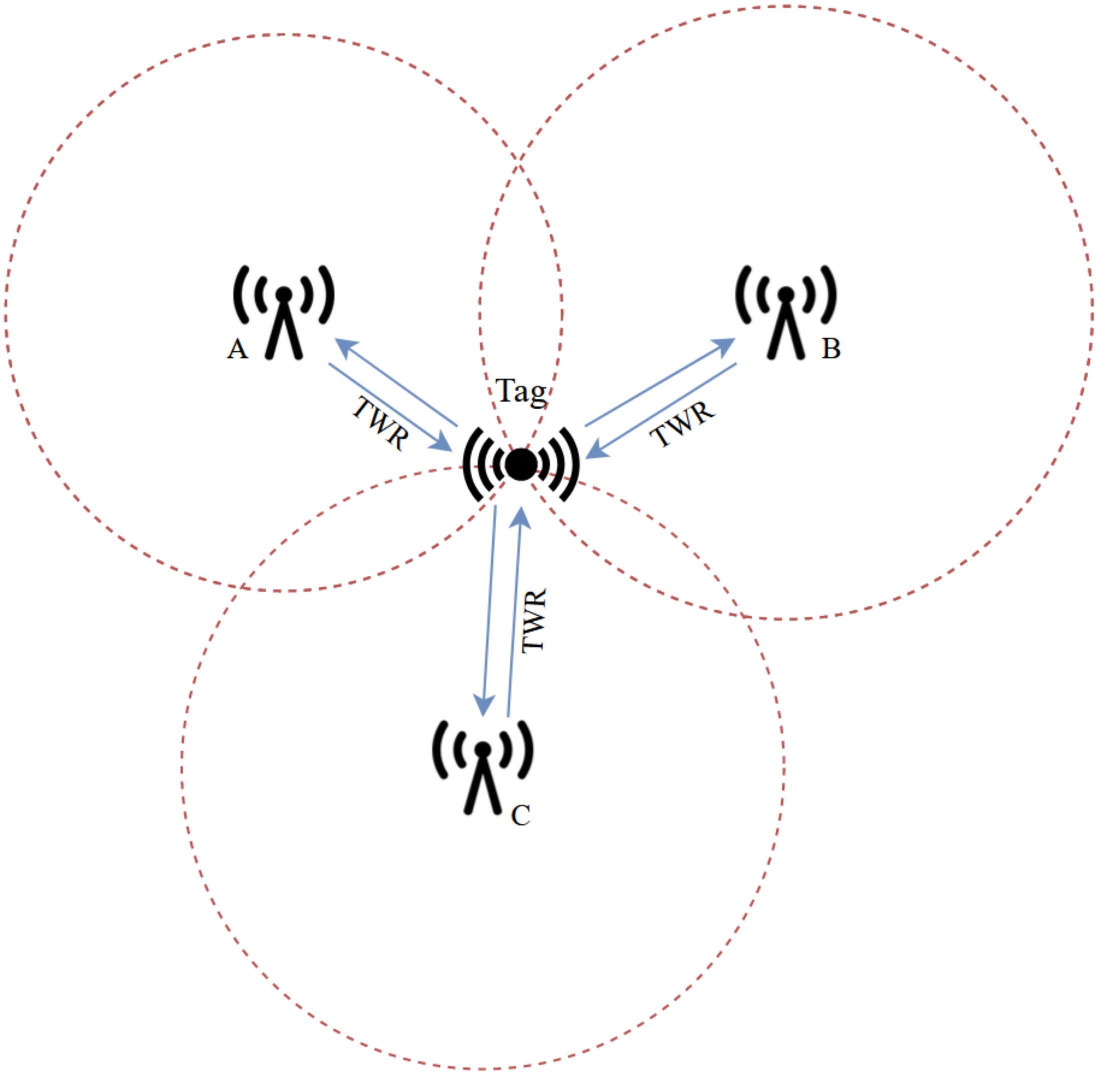


Figure 6: Trilateration can be used to determine the location of a tag with TWR measurements and three anchors: A, B and C

When ranging is performed with a single anchor the relative direction of the target is unknown. According to (Henry, 2023), the range measurement can be thought to form an imaginary sphere around the anchor on which surface the target could be anywhere. With a minimum of three anchors the distance measurements from each anchor intersect at the location of the target, so its position can be determined with trilateration. A minimum of three anchors is required for positioning in a 2D plane, for 3D positioning a minimum of four anchors is required.

A common way of implementing TWR based positioning systems is to have a select number of dedicated anchor devices that are installed at specific locations in some space, at the corners of a room for example. Since TWR measurements are performed individually between two devices, the anchors do not have to be as precisely synchronized as with TDOA measurements (see section 2.3.2). The anchors must exchange measurement data with each other and the host system within a reasonable time frame, since the target device may move between individual measurements. When considering the speeds of wireless communication, it would be easy for one to think it unlikely that a tag attached to a physical object would move at such high velocity that the update rate of the anchors would not be able to keep up with sufficient accuracy.

2.3.2 Time-difference of arrival

Time-difference of arrival (TDOA)[11] is based on measuring the exact moments in time where a signal arrives at different locations and use the time differences between those moments to determine the location of the target. Amendment 1 (IEEE, 2020b) describes two cases of TDOA:

- **Case 1:** a mobile target device periodically sends messages, referred to as “blinks”, that are received by multiple synchronized anchors. By comparing the TDOA at each anchor the system can determine the location of the target.

- **Case 2:** multiple synchronized anchors sequentially send a message that is received by a mobile device. The TDOA of those messages can be used by the mobile device to determine its location relative to the anchors.

TDOA provides a solution for situations where only the anchors or the tag need location tracking information and no other communication needs to happen between them. For example TDOA is a good solution for asset tracking with multiple available commercial solutions, often called real-time locating systems (RTLSs). Individual tracking anchors can be permanently installed to an indoor space and just receive and record blinks by multiple UWB tags and use TDOA to track the location of all of them in real time.

As (Henry, 2023) explains, positioning procedure itself is less straightforward with TDOA, unlike in TWR, the distance between anchor and target is not directly measured. Consider two anchors; A and B, within a known distance of each other. Suppose a signal arrives at A first and then at B after a few nanoseconds, since the speed of light and the distance between A and B are known it can be concluded that the signal origin must be a certain amount closer to A than B. The time-difference of arrival translates into a difference in distance which forms a hyperbolic line between A and B, on which the target could be anywhere. TDOA positioning systems require three anchors for positioning on a 2D plane and four anchors for 3D positioning, similar to TWR.

[11] Sometimes called one-way ranging (OWR)(IEEE, 2020b)(Henry, 2023).

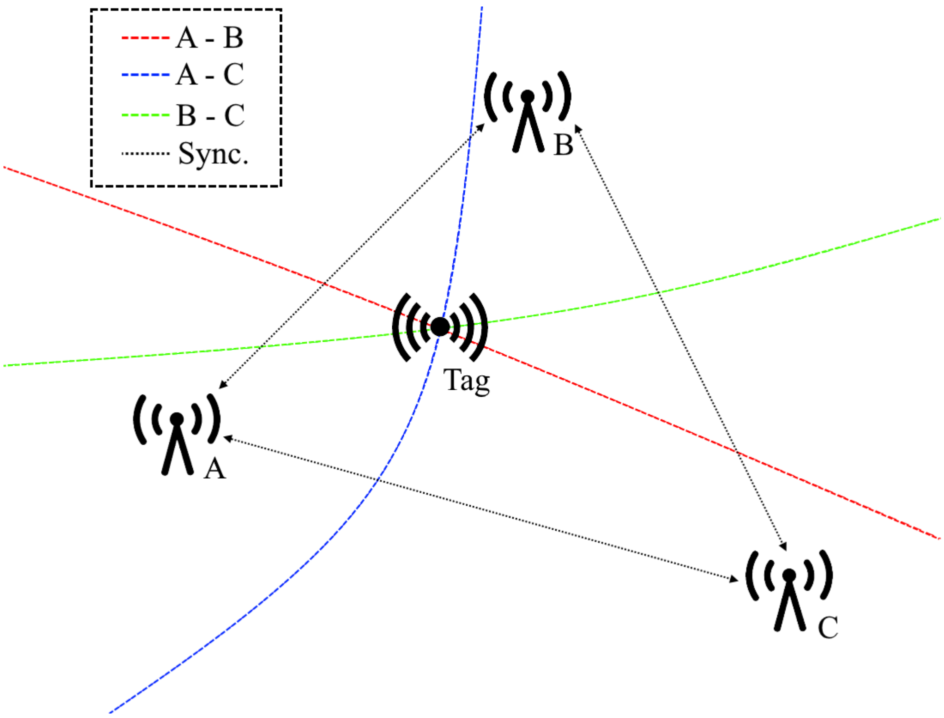


Figure 7: TDOA positioning of a tag with three synchronized anchors: A, B and C. Synchronization packets are often sent wirelessly.

A major challenge of TDOA positioning systems is that the anchors need to be precisely synchronized. Since radio signals move so fast and the positioning procedure with TDOA depends on comparing the timestamps of signals arriving at different anchors, even a small offset between the clocks of individual anchors can translate to large errors in the location data. Amendment 1 acknowledges this problem and suggests either wired synchronization of the anchors' clocks or using wireless synchronization messages exchanged by the anchors at fixed intervals, without commenting on the exact implementation (IEEE, 2020b).

2.3.3 Angle of arrival

According to (Henry, 2023), angle of arrival (AOA) is the angle at which a signal arrives relative to some target axis, typically formed by two or more antennas installed on some flat plane, a circuit board for example. UWB devices typically determined by measuring phase-difference of arrival (PDOA) at two antennas, PDOA is an expression of TDOA. With two antennas with a known distance between them and a known inbound signal frequency, determining the AOA is a fairly simple calculation:

$$\theta_y = \sin^{-1}\left(\frac{\Delta\varphi\lambda}{2\pi d}\right), \tag{2.5}$$

or

$$\theta_x = \cos^{-1}\left(\frac{\Delta\varphi\lambda}{2\pi d}\right), \tag{2.6}$$

where $\theta_{x/y}$ is the AOA depending on the reference axis, $\Delta\varphi$ is the phase difference between antennas, λ is the received signal's wavelength and d is the distance between antennas. A conceptual image of AOA is presented in figure 8.

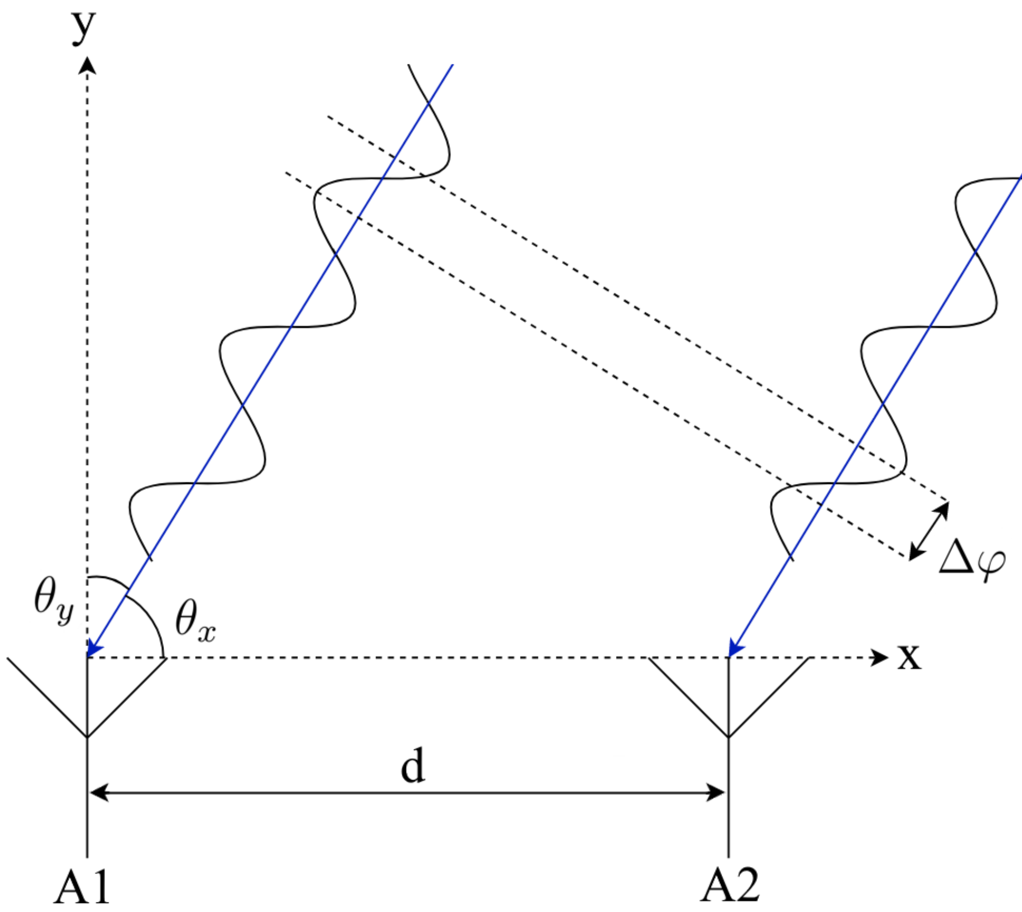


Figure 8: AOA between two antennas: A1 and A2 at distance d from each other. The AOA is calculated from the phase-difference of arrival, $\Delta\varphi$.

Referencing against the y-axis in figure 8 the AOA should fall between $-\frac{\pi}{2}$ to $\frac{\pi}{2}$, this means that in order for equation 2.5 to have a single solution the maximum distance between antennas must be equal to or shorter than $\frac{\lambda}{2}$, otherwise the AOA measurement becomes unreliable (Dotlic et al., 2017). Additional guidelines for antenna design are covered in chapter 3.

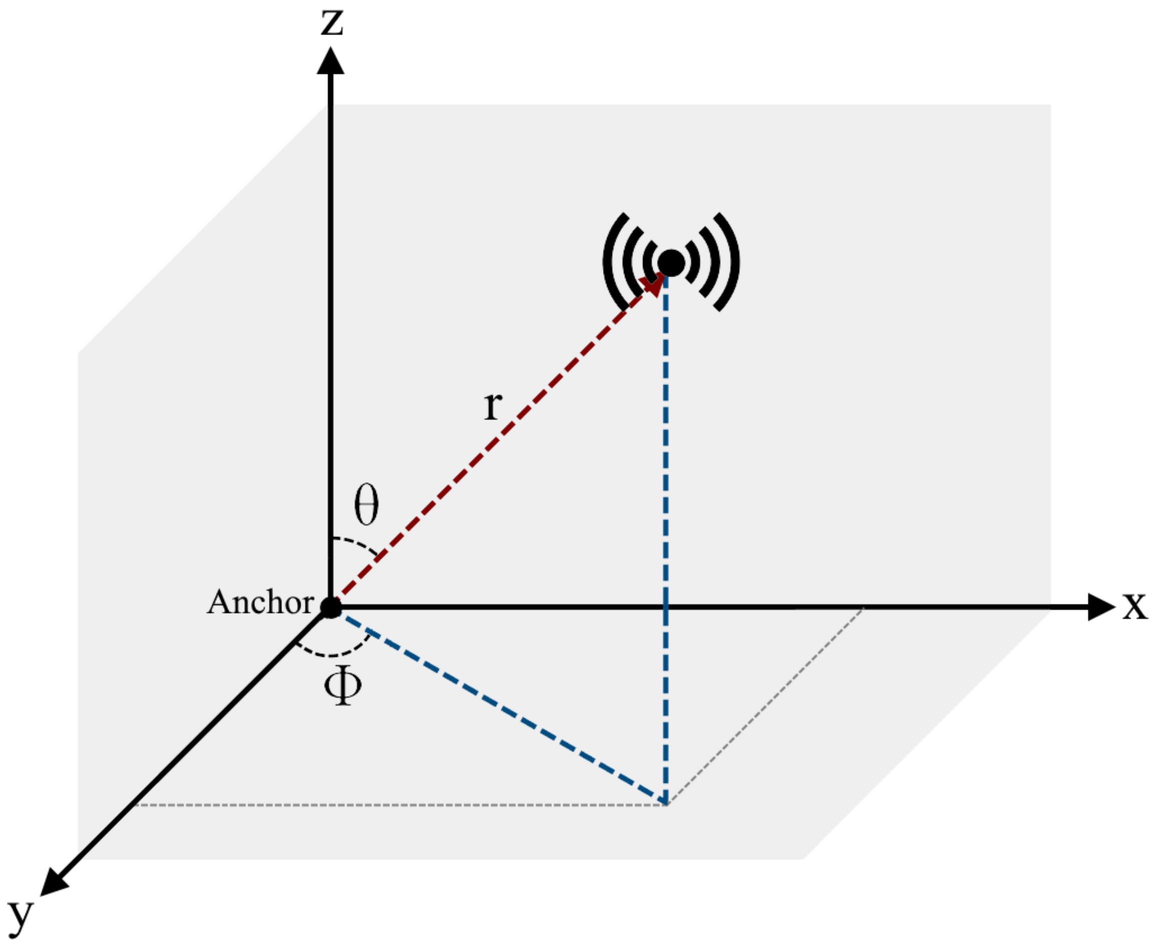


Figure 9: 3D AOA estimation of a target at distance r with elevation θ and azimuth Φ angles.

Typically AOA is measured with two antennas, 3D AOA can be obtained by adding a third antenna on an axis perpendicular to the other two so that the elevation and azimuth angles can be measured separately (see figure 9) (Henry, 2023). Support for azimuth and elevation AOA data is included in 802.15.4z. A single AOA measurement is not enough for positioning, it yields only a vector of unknown length, pointing at the target. Positioning is usually achieved by measuring the range to the target (r in figure 9) with some form of TWR, when the range and AOA are known, determining the location of the target is a matter of basic geometry.

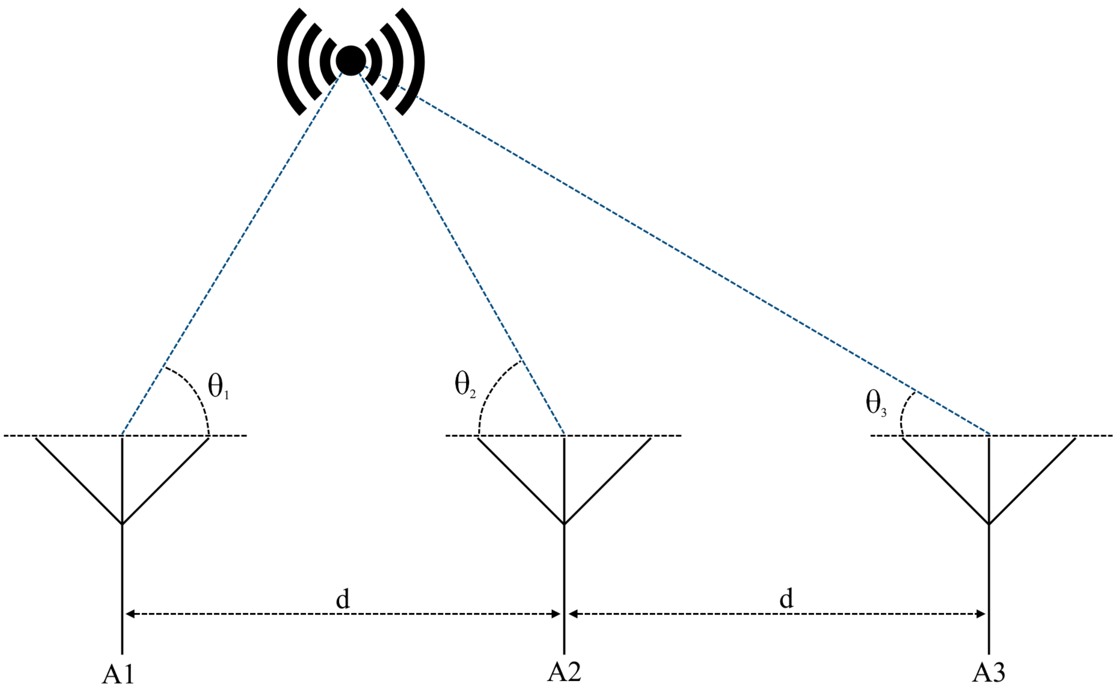


Figure 10: Triangulation of a target with three AOA measurements at locations A1, A2 and A3

Another way of achieving 2/3D positioning with AOA is to take advantage of multiple AOA measurements from different locations, after which triangulation can be used to determine the location of the target (Elsanhoury et al., 2022). A conceptual image of this is presented in figure 10. This method has the advantage of allowing positioning with unidirectional messaging, i.e., the anchors don't to send messages to the target, which is a more flexible solution from a regulatory standpoint. On the other hand, this kind of positioning system would require multiple antenna arrays with some distance between them, potentially raising cost and making the system take up more space.

3 DESIGN AND PLACEMENT OF UWB ANTENNAS

From the electrical point of view, the process of designing a basic antenna is well established by science and will not be extensively covered beyond the desired electrical characteristics for UWB.[1] The objective of this chapter is to identify the antenna design criteria that are specific to UWB positioning applications. As was stated in the introduction, the emphasis on the placement of antennas relative to the environment and to each other, as well as the mechanical dimensions of the antennas.

First the antennas' basic electrical requirements and their relationship to their dimensions are covered. Then, the scope is expanded to placement of antennas for different positioning techniques and relative to the surrounding environment. A short introduction to microstrip patch antennas (MPAs) and their core components is included in section 3.4, as it seems to be the most popular way of implementing antennas in modern UWB systems, and because the development kit used for the experimental portion of this thesis uses MPAs in its antenna solution.

3.1 Electrical requirements of UWB antennas

The main obstacle for UWB antenna tuning is the bandwidth that is required for the technology. As discussed in sections 2.1 and 2.2, UWB devices typically operate on the frequency band of 3.1 GHz and 10.6 GHz with multiple distinct channels on that band, with bandwidths of 500 MHz or above. Depending on the intended operating channels, an UWB antenna may have to achieve up to 7.5 GHz of bandwidth, which usually is not a major design consideration with traditional narrowband technologies. The bandwidth of an antenna is usually defined in terms of what is the frequency range at which the antenna is well matched to its feed, this range is known as the antenna's impedance bandwidth (Chen and Chia, 2005). The impedance bandwidth is defined either by the antenna's S-parameters, usually return loss (S_{11}), or by voltage standing wave ratio (VSWR). Usually, the target values for VSWR are 2 to 1.5 and less than -10 dB to -15 dB for return loss, in the whole operating range (Chen and Chia, 2005).

Amendment 1 (IEEE, 2020b) defines specific UWB pulse properties that compliant devices need to fulfill, for the HRP PHY the reference pulse shape is that of an 8. order butterworth pulse with a 3 dB bandwidth of 500 MHz, the pulses transmitted by a compliant device

[1] Section 3.1 is not intended to be a complete review of the electrical properties of UWB antennas, rather it's purpose is to provide context and point the reader to the right direction.

have to resemble this shape to a certain degree. The electrical characteristics of the antenna should not interfere with the pulse shape to such a degree that compliance with the standard is compromised. According to (Srifi, 2011), the antenna should have uniform gain and a uniform radiation pattern across its intended operating band. A poorly designed antenna may significantly reduce the system's ability to accurately send pulses and interpret inbound ones. The antenna should have a linear phase response, so the group delay remains constant, this helps to prevent distortion in the transmitted and received pulses. In a nutshell, non-linear performance of the antenna may induce significant errors in communication and compromise the systems ability to conform to the requirements of Amendment 1 and local PSD limits for UWB devices.

3.2 Mechanical properties

There are a few components of the mechanical antenna design process which are more emphasized in UWB applications than in traditional narrowband systems, such as Bluetooth and WiFi. Some arise from the nature of the technology itself and others from the applications that usually take advantage of UWB. Some positioning and ranging techniques have their own issues specific to them, such as matching the feed lines of the antennas for AOA applications.

3.2.1 Antenna dimensions

Over its history the antennas used for UWB have appeared in different shapes and sizes. Today however, UWB is especially popular in small scale embedded systems and portable applications, like smartphones and asset tracking tags. Not just any antenna is going to be practical in these kinds of applications where the antenna may easily be the single largest component of the device. In embedded systems and especially in mobile applications the size constraints for the antenna may be rather extreme: the available space may be in the ballpark of just a few millimeters in each direction. It is desirable for the antenna be able to be mounted onto a circuit board without the need for cabling or other external components, or directly etched on the board itself, which seems to be one of the more popular methods in most portable devices with wireless capabilities.

3.2.2 The feed line

The dimensions and electrical properties of the feed line, the conductor that connects the antenna to the UWB transmitter, are critical for positioning procedures where the measurement process is based on comparing the relative signal arrival times at different locations. It is important, particularly for AOA, that in a system of multiple anchors/antennas the feed lines are matched. A combination of hardware level matching and software calibration is recommended to achieve the most accurate results.

As for AOA, it was established in section 2.3.3, that the distance between individual antennas must be equal to or less than half of its intended channel's wavelength. For example, the half-wavelength distance for HRP PHY channel 9 would be 18.78 mm. In essence, AOA relies on the device's ability to measure the time a signal traveling at the speed of light takes to propagate a distance not much more than a couple dozen millimeters at the most. Even if the antennas are correctly spaced, from this requirement arises another critical problem that has to be accounted for in product development: length matching of the feed lines. Individual antennas are connected to the transceiver and processor by a feed line of a certain length. When a signal reaches an antenna it does not just instantly jump to the processor, it has to travel along the feed line, this takes time. A difference in feed line length of just a couple millimeters can cause an AOA error of several degrees. An error in AOA, when combined with ranging causes an error in positioning that is directly proportional to the distance of the target, which can result in huge errors as the target gets farther away. Furthermore, the electrical characteristics for all antennas should be as identical as possible. Mismatches may distort the received waveform on the path towards the processor, this can interfere with the PDOA measurement that AOA relies on, resulting in incorrect AOA calculation.

The same is true to some extent for systems utilizing TDOA or TWR in their positioning solution, the antennas of each node should have the same characteristics to reduce unnecessary errors. However, the anchors in TDOA systems do not have to be within millimeters of one another, commercial TDOA positioning systems typically consist of a set of independent anchor devices that are placed around a much larger space. Therefore, a mismatch of a couple millimeters in antenna feed lines generally should not cause as such a large error, as the actual distances being measured are typically a couple orders of magnitude larger. However, this is true under the assumption that the mismatches of individual feed lines is in the order of millimeters, should the difference in length be centimeters or even meters the potential for error grows. The same goes for TWR based systems, the time it takes for the signal to propagate from the antenna to the transceiver and processor should be accounted for in the ranging procedure.

3.3 Antenna placement and the environment

When designing a positioning system with multiple anchor points their relative locations are an important design consideration. While some are hard requirements that are a direct result of the mathematical basis of the algorithm, like antenna spacing with AOA. With TDOA and

TWR comes more flexible antenna placement but these systems have their own issues that need to be taken into consideration in their design process.

3.3.1 Antenna placement with AOA

The placement of individual antennas for AOA described in section 2.3.3 is straightforward: two antennas, a half wavelength apart for 2D AOA, add a third antenna on a perpendicular axis for 3D AOA. Difficulties arise mainly from antenna orientation relative to the target and when placing multiple arrays to leverage multiple AOA measurements for triangulation. The accuracy of AOA varies depending on the actual angle between anchor and tag, for example (Juran et al., 2022) found that the error in AOA measurements increases as the real angle increases, errors of up to 16° were measured at a -45°. The measurements performed in this thesis also found the largest errors at higher angles in a free space scenario, materials in front of the antenna were found to vastly increase AOA's deviation from the expected values. Therefore, when implementing AOA based positioning devices, the normal of the antennas' plane should be pointed directly at the center of the target area to ensure best coverage. Also when placing multiple arrays for triangulation purposes they should be spaced with enough distance between one another so that the AOA vectors converge on a smaller area. Additionally, with multiple arrays the host system needs access to the arrays' relative locations to perform the necessary trigonometry for locating the target.

3.3.2 Antenna placement with TDOA

The anchor placements in a TDOA positioning system is critical for positioning accuracy. TDOA suffers from geometric dilution of precision (GDOP), which is a well known drawback of traditional TDOA based geolocation systems (MathWorks Inc., 2021). The same problem is present for UWB TDOA, as is evident from the research conducted by (Grasso et al., 2022). When tracking a target on a 2D plane, the region where the system is most accurate is within the convex hull formed by the anchor points. When moving outside of this range the accuracy of positioning rapidly decreases.

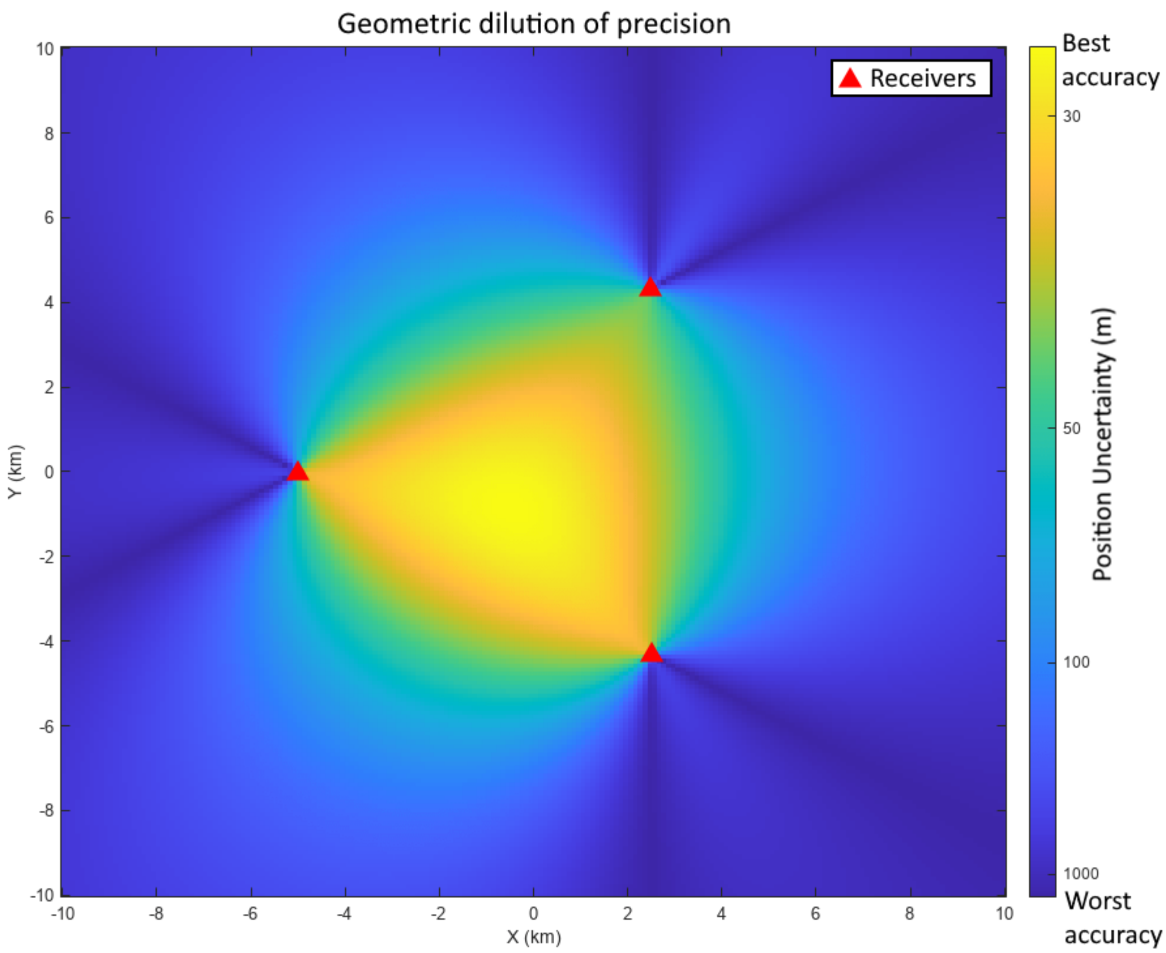


Figure 11: The accuracy of TDOA deteriorates outside the envelope of the anchors (red triangles) due to geometric dilution of precision (modified for better clarity from MathWorks Inc., 2021)

Figure 11 illustrates the accuracy of a TDOA positioning system relative to anchor placement. The original context for this graph is ”traditional” large scale geolocation systems as is evident from the units of measurement used. The exact numbers are not important here, the point is to illustrate the effects of GDOP. The concept is the same for UWB, a detailed report on the effect for UWB TDOA specifically can be found in (Grasso et al., 2022). Note that the beforementioned report only considers TDOA accuracy on a 2D plane. Section 7 of (Debany, 2021) found that TDOA accuracy varies as a function of the target’s altitude relative to the sensors, however that report is not about UWB. While the system can retain some accuracy outside the anchors’ perimeter, for most practical cases this means that the target area for tracking has to be surrounded by anchors to function properly. Generally this seems to be the case for commercial TDOA based positioning systems, anchors are placed at the corners of some indoor space close to the ceiling for better line of sight and are used to track assets within that space.

Another noteworthy thing when implementing TDOA positioning is the that in order to function, the system has to have access to the positions of the anchors within the target space and relative to each other. Furthermore the synchronization issue described in 2.3.2 should be taken into account when placing anchors, so that the environment doesn't interfere with the synchronization procedure. Also when placing the anchors they should be separated from one another by a suitable distance, (Zhang et al., 2022) found the minimum separation to be around 3 meters. The smallest measured TDOAs were around a few nanoseconds and the synchronization errors were measured at around half nanoseconds on average. Based on this it can be concluded that when TDOA measurement points get closer to each other the ratio of synchronization error to measured TDOA increases, therefore deteriorating the accuracy of the system.

3.3.3 Antenna placement with TWR

TWR positioning systems have similar requirements to TDOA in terms of anchor placement. Anchors are often placed on the same plane that is elevated from the target area for improved line of sight. The coordinates of the anchors need to be known and the system calibrated accordingly, same as with TDOA. Also following the same pattern, TWR has been found to suffer from poor accuracy in the third dimension, but in the grand scheme of research and commercial applications the 3D positioning capabilities of TWR remain relatively unexplored (Zhou et al., 2022).

For the purposes of embedded applications the space requirements of a positioning system of any kind are a key design factor. For TDOA the before-mentioned 3 meter minimum anchor separation should be a safe bet. For TWR this information doesn't seem to be readily available. An educated guess can however be made, based on the typical ranging accuracy of TWR. Generally speaking both TDOA and TWR advertise a positioning accuracy of around 10 to 30 cm (Zhang et al., 2022). This indicates that the separation between measurement points should be considerably larger than that error margin, which would make designing a compact positioning system difficult without some novel solution.

In some situations it may be necessary to limit the tracking target area with additional measures to avoid false location measurements. Consider a TWR based positioning system with some number of anchors mounted at the ceiling level on the first floor of a two story indoor space. The distance to each anchor from a tag is measured individually which forms a sphere of possible locations around each anchor, the target is going to be where all these spheres intersect. However, if the tag isn't on the same plane as the anchors, which probably is the case in this configuration, the range measurements intersect above and below the anchors' level. This means, that based on TWR data alone the system would have no way of knowing whether the target is on the first or the second floor as illustrated in figure 12.

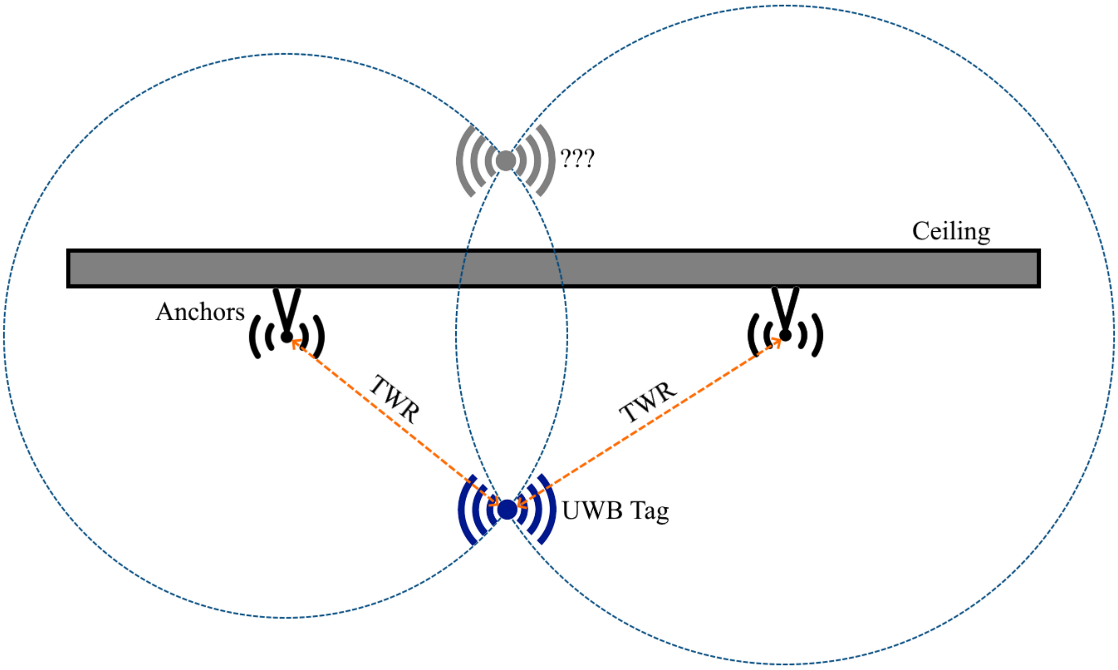


Figure 12: The elevation of an UWB tag may have multiple different solutions in TWR positioning systems with coplanar anchors.

There are software solutions for identifying position data coming from wrong rooms/floors, for example, determining whether the signal was received from a path of direct line of sight to the target using machine learning or different filtering algorithms (Henry, 2023). Problems with unwanted positioning signals can be further alleviated in hardware by improving the directivity[2] of the antenna so that signals coming from outside the target area are already attenuated at the antenna level. Directional antennas make distinguishing a legitimate signal from outsiders easier.

3.3.4 External factors

One of the reasons UWB is so popular in indoor positioning systems is that it can operate reliably in locations where GPS struggles due to the signal path being obstructed: inside buildings and dense urban areas. UWB is not immune to these non-line-of-sight (NLOS)

[2]The ratio of the radiation intensity in a given direction from the antennas to the average radiation intensity in all directions (IEEE, 2013).

conditions either, which is another big challenge for UWB, and these issues are arguably even more prevalent in indoor spaces: walls, doors and furniture are everywhere. The best positioning performance is achieved with a direct line-of-sight (LOS) between transmitter and receiver. NLOS situations often make measured distances appear longer than they actually are. When the direct path between participating devices is obstructed, the primary signal is attenuated or blocked completely, see figure 13. According to (Marano et al., 2010), in these situations one of two things usually happens. If the NLOS -path signal can still be detected, the measured TOF can be off due to the NLOS propagation speed being slower than it would be in open air with direct LOS. If the NLOS signal is attenuated to the point it can't be detected by the receiver, a reflected signal with a considerably longer path can be detected, which again causes the measured TOF to be longer than it should be. Even if UWB is considered particularly resilient to multipath it doesn't help much if the primary signal is completely blocked.

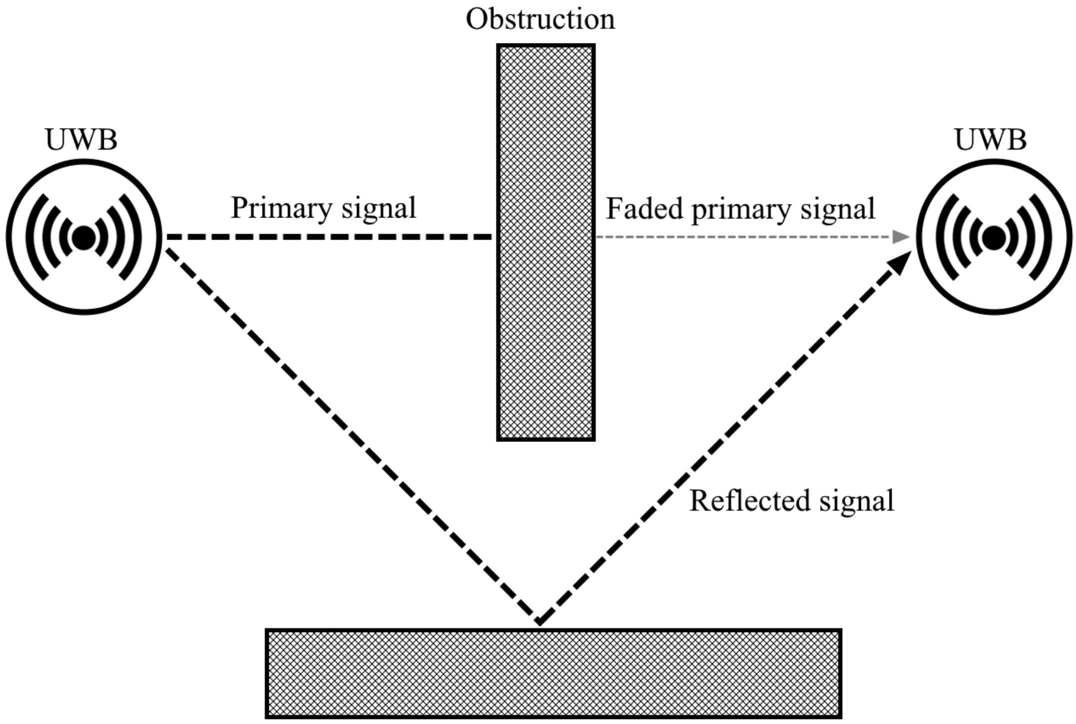


Figure 13: The primary signal that the positioning procedures rely on can be attenuated or blocked completely by obstructions in the signal path, leading to NLOS propagation.

NLOS conditions can severely deteriorate the system's ability to reliably track its targets. Positioning systems with TWR or TDOA algorithms can easily experience errors of several meters, when NLOS propagation is present (Tiemann et al., 2022)(Prorok et al., 2011). In chapter 5 of this thesis, AOA was found to be much more vulnerable to NLOS propagation issues, compared to TWR at least. The first step to mitigating issues with NLOS, is designing and deploying the hardware in a way that minimizes the likelyhood of NLOS propagation, a common way to do this is to install individual anchors at elevated positions to provide better coverage in the target area. It's also worth remembering NLOS propagation when designing the enclosures for UWB devices, even if the receiver is enclosed in thin plastic it still technically results in NLOS propagation. Especially with AOA not only should the device enclosure not significantly interfere with the UWB signals in the first place, but the properties of the enclosure should be uniform in all directions of interest, so that the enclosure wouldn't cause differences in the signals received at individual antennas. The effect of different materials in the immediate vicinity of the antennas, which typically means their enclosure, on AOA and TWR is the main goal of the measurement campaign of chapter 4.

Of course there is no perfect hardware level solution for mitigating problems caused by NLOS propagation. Even if a system is deployed so that all anchors have perfect LOS coverage everywhere in the target area, the system only works for that specific environment and has to be carefully reconfigured if the conditions in the target location change. NLOS issues are often mitigated by software that can vastly improve the accuracy of positioning in NLOS conditions, these solutions often include methods like digital filtering or machine learning algorithms, which are designed to detect and compensate for NLOS effects (Henry, 2023).

3.4 The microstrip patch antenna

In today's UWB applications the microstrip patch antenna (MPA) is clearly the most popular antenna design (Kumar et al., 2021). This is probably due to the fact that MPAs can be etched directly on a printed circuit board (PCB); they have a small footprint and they are very cheap and easy to manufacture and prototype.

In its simplest form an MPA consists of a rectangular or elliptical patch connected to a feed line of some form and a ground plane, separated by a dielectric substrate. A simple rectangular MPA is presented in figure 14, typically the frame which MPAs are built on is just a regular PCB. An antenna system may consist of a single MPA or multiple MPAs may be connected to an antenna array, the patch shape and size can be altered to fine tune its parameters, same goes for the feed line. There is a large number of possible configurations with different properties but the most basic MPA is just a rectangular patch, as illustrated in figure 14.

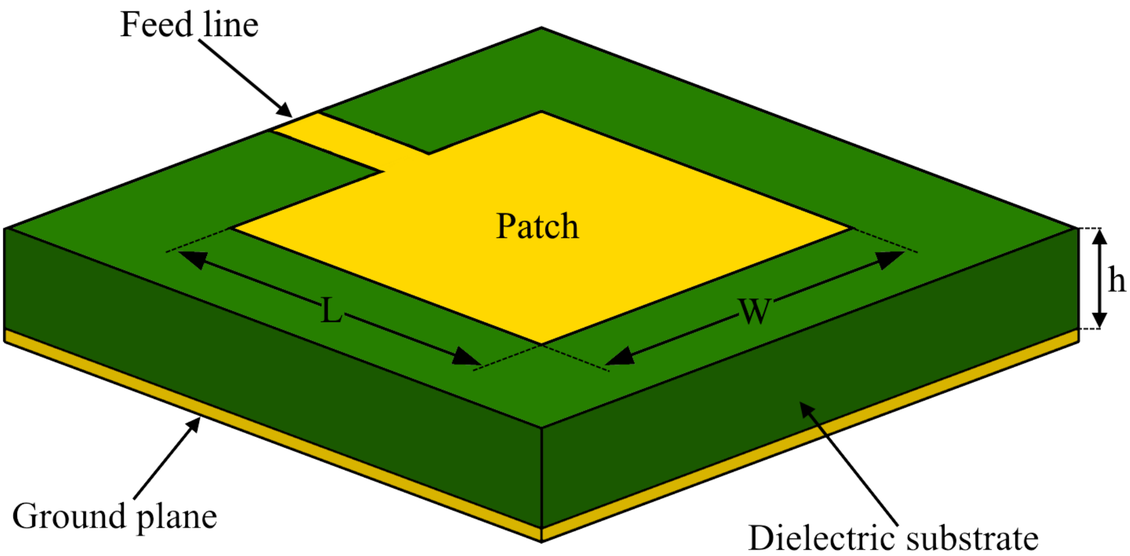


Figure 14: A patch antenna typically consists of a microstrip patch and a ground plane under it with a dielectric substrate between them.

The fine details of the design process of individual antennas are out of the scope of this thesis, though. For additional information on the analytical basis for MPAs and their design methodology, refer to "*Smart antennas: Latest Trends in Design and Application*" (Malik et al., 2022) or "*Broadband Planar Antennas: Design and Applications*" (Chen and Chia, 2005) for example. Besides, the use of professional design tools is recommended in serious design work.

3.4.1 Patch dimensions

In the case of a basic MPA the width and length of the patch depends on the operating frequency and the properties of the dielectric substrate. The length of the patch (L in fig. 14) is always the non-radiating edge and the width (W in fig. 14) is always the radiating edge (Das et al., 2022). The dimensions of a rectangular patch can be determined with the following equations:

$$W = \frac{c}{2 \times f_0 \times \sqrt{\frac{\varepsilon_r + 1}{2}}}, \tag{3.1}$$

$$L = \frac{c}{2 \times f_0 \times \sqrt{\varepsilon_{\text{eff}}}} - 2 \times \Delta L, \tag{3.2}$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_{\text{r}} + 1}{2} + \frac{\varepsilon_{\text{r}} - 1}{2} \times \left[1 + \frac{12 \times h}{W}\right]^{-\frac{1}{2}}, \tag{3.3}$$

$$\Delta L = 0.412 \times h \times \frac{(\varepsilon_{\text{eff}} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{\text{eff}} - 0.258)(\frac{W}{h} + 0.8)}, \tag{3.4}$$

where c is the speed of light, f_0 is the operating frequency, ε_{r}, is the dielectric constant of the substrate, ε_{eff} is the effective dielectric constant of the substrate, ΔL is the extended length and h is the thickness of the substrate (Das et al., 2022).

When the dimensions of a patch are plotted for the whole UWB band from 3.1 GHz to 10.6 GHz in figure 15, it can be seen that the dimensions of the patch decrease as the frequency increases. By altering the substrate thickness the length of the pad changes by a small amount, the substrate thickness is noted in parentheses next to length in the legend. These graphs were calculated with the substrate's dielectric constant at 4.8, which corresponds to FR4 material. It should be remembered that these are just the dimensions for a simple rectangular patch with no additional features, when optimizing an antenna for real world applications the antenna could take a more complex shape.

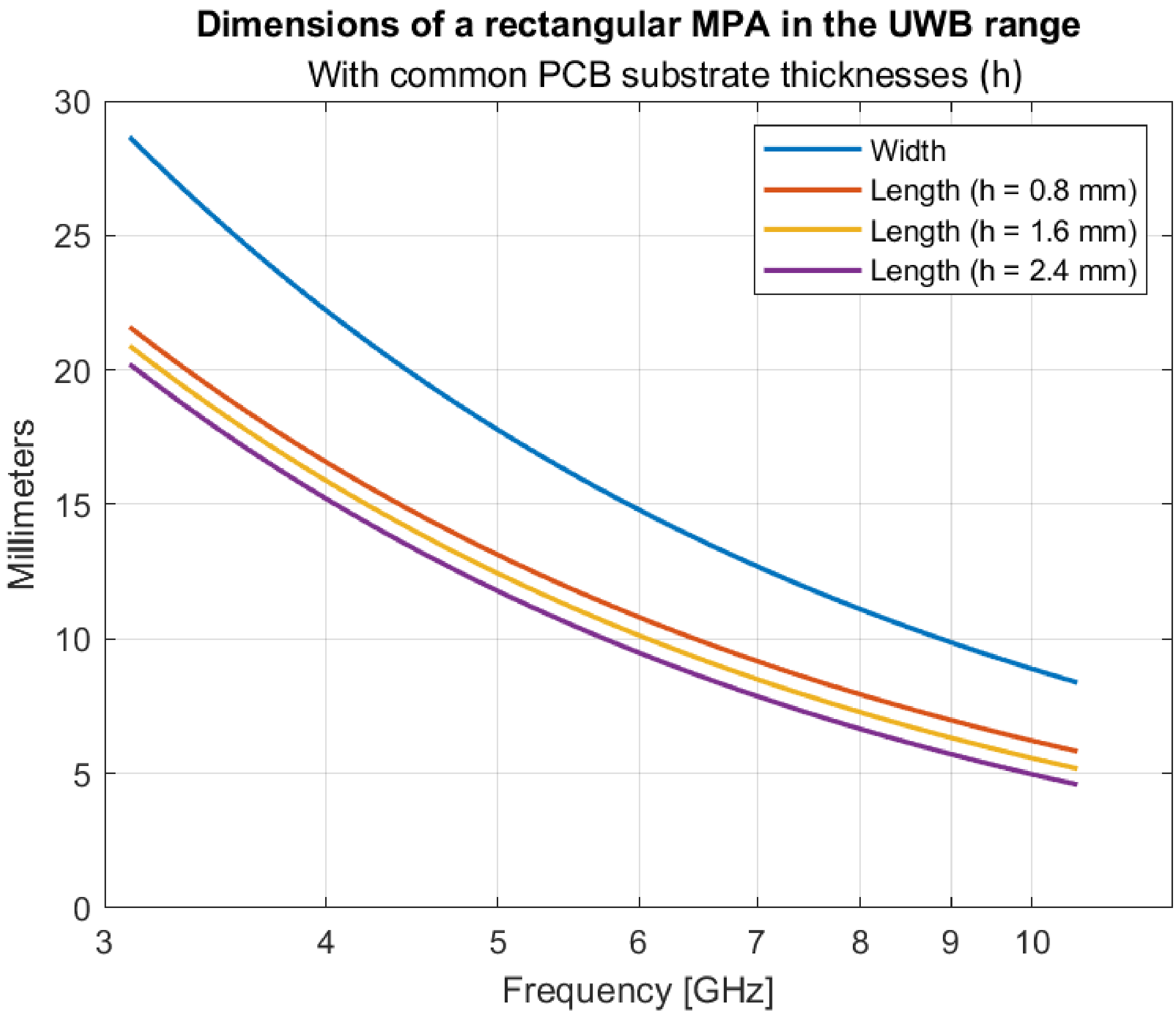


Figure 15: The dimensions of an MPA are dependent on the channel frequency and substrate thickness.

An example calculation for channel 9 of the Amendment 1 HRP PHY band is included in appendix F, both the dimensions for a single rectangular patch and a 3 patch array for 3D AOA measurements are calculated. For channel 9 (7987.2 MHz), which is the only mandatory channel in high band HRP PHY, a single patch would have a width of 11.03 mm and a length of 7.10 mm, which is a very manageable size even for a small device. For a 3D AOA configuration the dimensions for the whole array are 25.88 mm $\times$ 29.81 mm, in addition to these, some extra space around the antennas is required for the ground plane. While serious design work is almost certainly a more complicated process than presented here, this example should provide a decent approximation of the size class one could expect MPAs to be.

3.4.2 Feed line options

The other main component of an MPA is the feed line that it's connected to the transceiver with. There are four common feeding methods illustrated in figure 16, which are clockwise from top left: microstrip line feed, coaxial feed, aperture coupling and proximity coupling (Das et al., 2022). Of these the first two seem to be the most popular options in literature, maybe because of their simpler design.

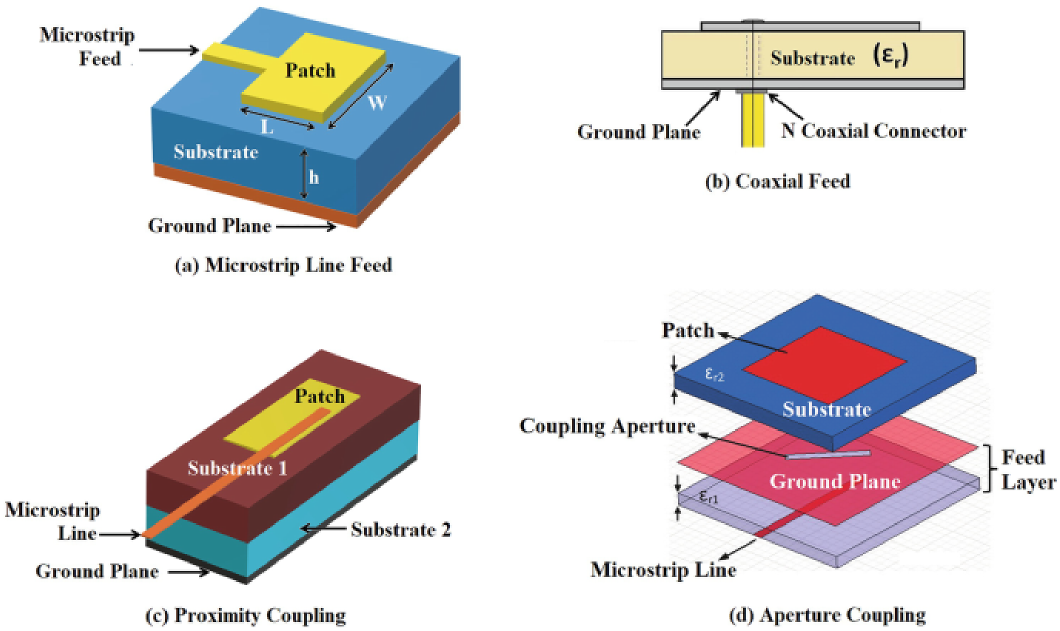


Figure 16: The four basic feeding techniques for MPAs. (Das et al., 2022)

Some generalizations about the performance of these designs can be made, for example: aperture coupling is supposedly better for wider bandwidth while the coaxial feed method has higher return loss, according to (Das et al., 2022). However, this doesn't mean that any one of these designs is the best and only choice for UWB. For instance, the UWB development kit used in the experimental portion of this thesis uses an array of three rectangular patches with coaxial feed lines in its antenna solution, even though the coaxial feed supposedly has a narrower bandwidth. There is a myriad of steps that can be taken to improve the bandwidth of an MPA, that are beyond the scope of this thesis. In a nutshell, wider bandwidth is usually achieved by introducing multiple resonances and/or impedance matching. Popular methods include adding parasitic radiators next to or on top of the primary patch, altering the shape of the patch with slots and notches or adding an impedance matching network to the feed line. More information on wideband MPA techniques can be found in (Chen and Chia, 2005) and (Sharma, 2022).

4 EXPERIMENTS WITH TWR AND AOA

A series of experiments were performed with the help of an UWB development kit. The goal of these tests was to evaluate the capabilities of an UWB positioning anchor a situation where it's embedded in furniture or where the signal path to its antennas is otherwise obstructed. This was achieved by performing a series of baseline measurement in a free space scenario and using them as reference point for more challenging environments for the device under test (DUT). The available equipment restricted the measurements to AOA and TWR, therefore TDOA positioning could not be experimentally tested. The overall objective of this measurement campaign was to obtain experimental data to aid in the design of the enclosure of an UWB positioning anchor and the placement of its antennas. The measurement setup, available equipment and the measurements themselves are described in this chapter, the results are presented and analyzed in chapter 5.

4.1 Equipment and measurement setup

We used a development kit with out-of-the-box UWB capability, which includes both the anchor and two tags. In addition to the UWB devices themselves, some way of determining the actual position and orientation of the DUT relative to its counterpart was needed, as well as some method of positioning the participant devices within the test environment.

4.1.1 The UWB kit

The UWB development kit, which was used for the measurements in this thesis was the MK UWB Kit SR150/SR040 by (Mobile Knowledge, 2023b). The set includes an "MK UWB Shield" on which various different UWB antenna modules can be attached to and a pair of UWB tags. The main component that was tested was the included "MK UWB 3D Antenna board" which featured the Trimension™ SR150 UWB chip by NXP, this device served as the anchor for the UWB positioning and will be henceforth referred to as the DUT. This module is capable of DS-TWR and 3D AOA measurements (Mobile Knowledge, 2023a). The tags on the other hand were based on the SR040 UWB chip from the same product line. An image of the 3D Antenna Board and the UWB Shield is presented below, an enclosure was 3D printed for the assembly to protect it's electronics and for mounting the setup to a tripod.

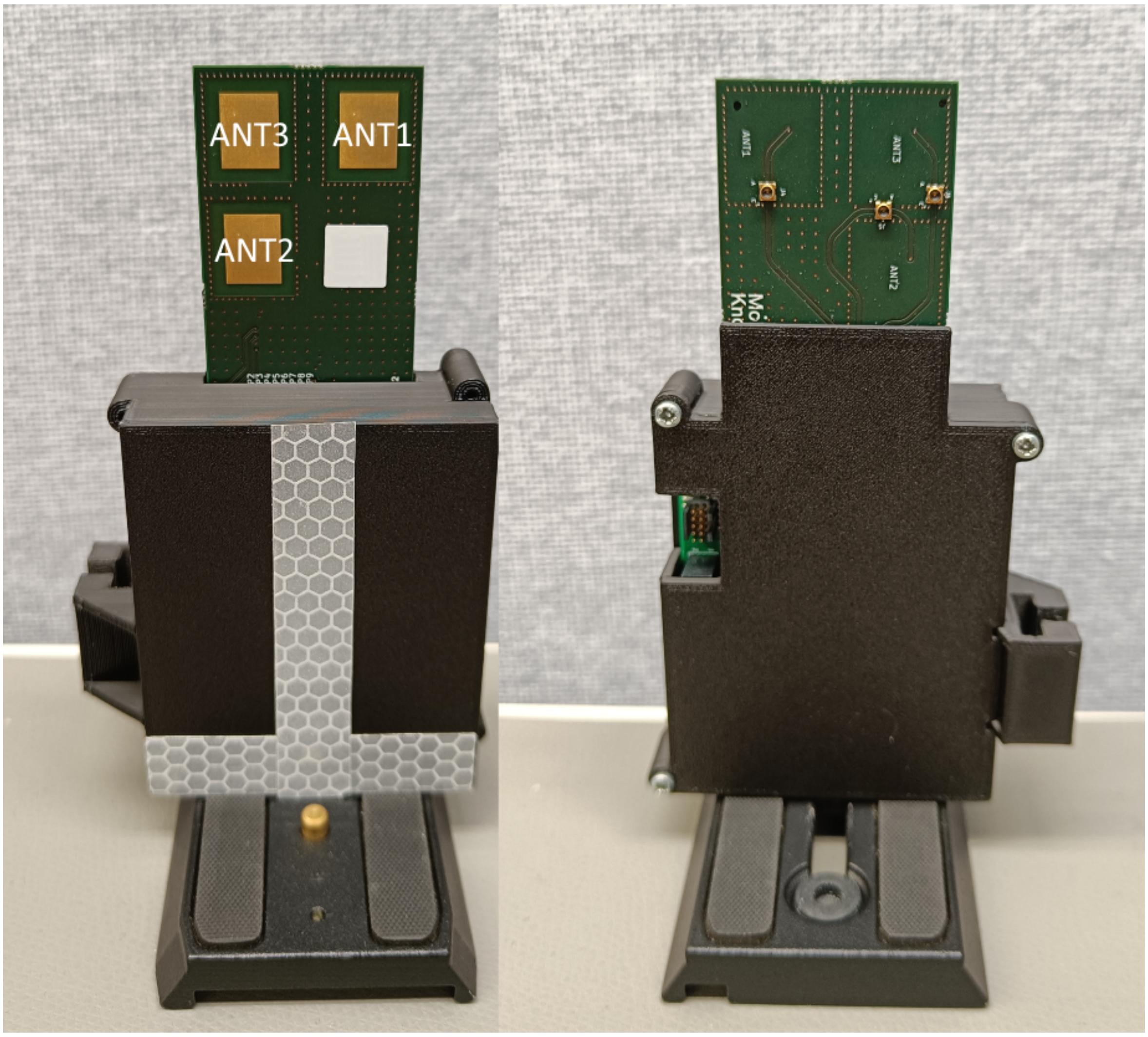


Figure 17: The MK UWB 3D Antenna Board connected to the MK UWB Shield in a 3D printed enclosure. The front of the device is on the left, the back side on the right.

The features that were tested in this thesis were the antenna board's ranging and 2D AOA capabilities.[1] The measurement data was gathered with the included "UWB PC Shell" application, the software or firmware were not modified in any way from the default factory versions. The device communicates on HRP PHY channel 9, which is around 8 GHz (Mobile Knowledge, 2023b). The AOA was measured relative to the horizontal axis, which is defined by the top two patch antennas in figure 17. Antenna number 3 is the reference point for AOA and ranging, it is the top left patch on the left side (front view) figure 17 (Mobile Knowledge, 2023a). The software and documentation of this development kit are not publicly available.

[1] 3D AOA isn't enabled by default and requires modifications to the shield's firmware.

4.1.2 The measurement setup

Two different camera tripods were modified so that the DUT and the tag could be securely mounted on them, these tripods were used to set the placement and orientation of the participating devices. Two things needed to be considered here, the actual real-world distance between the DUT and the tag, and the DUT's angle relative to the tag. The tag had to be placed in a way that its UWB antenna is perpendicular to the center point between the top two antennas in figure 18, in this position the measured AOA should be zero degrees.

The distance between the DUT and tag was measured with a laser distance meter, P2802 from PeakTech, which is capable of measuring distances of up to 80 meters with $\pm$ 2 mm accuracy, according to the included calibration certificate. The P2802 was mounted to the side of the DUT assembly as presented in figure 18. The offset from the center point of the antenna array to the laser beam was mirrored on the tag's side and a reflective target was placed in that position to aid with orienting the anchor correctly, as presented in figure 19. Since aiming a single laser beam towards the tag proved to be challenging at longer distances, reflective tape was used to add crosshairs to both the DUT and tag assemblies. A laser level could then be used to find these tape strips to make placing the DUT and the tag perpendicular to one another a lot easier. A way of accurately adjusting the azimuth and elevation angles of the DUT wasn't readily available, so protractor discs were 3D printed to allow manual adjustments with reasonable accuracy.

Figure 18: Protractor discs were 3D printed for easier adjustment of the azimuth/elevation angles. A laser distance meter was mounted to the side of the main DUT enclosure.

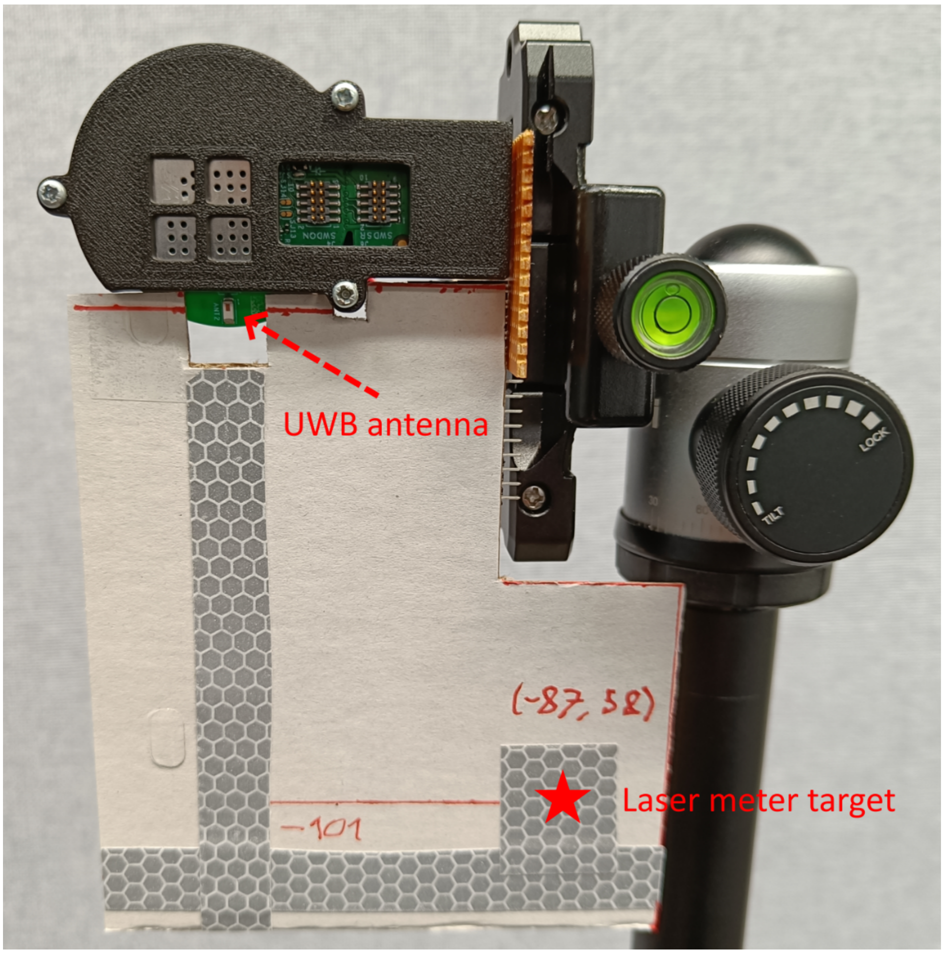


Figure 19: The tag was mounted to a camera tripod similar to the DUT. Reflective tape was used to add crosshairs to improve laser visibility when positioning the tripods.

These tripods provided easy placement and manipulation of the DUT and tag but weren't the most ideal solution in terms of accuracy. The distance between these devices could be determined accurately enough, the orientation of the DUT and the tag is where uncertainty is most obvious. Firstly the angle adjustments must be done by hand, which is sufficient when working with relatively large angle increments but quickly gets unreliable when approaching sub 5° adjustments. Secondly getting the tripod head to be completely level has proved somewhat challenging, this caused the elevation angle of the DUT to drift when adjusting the azimuth angle, since its axis of rotation is determined by the orientation of the tripod. Furthermore, a minor flaw of the laser method when positioning the tripods themselves was that it didn't account for any offset in the orientation of the tag. The angle of the tag's antenna, meaning the plane formed by the cardboard sheet in figure 19, could easily have been several degrees off relative to the DUT's antenna array.

4.2 Baseline ranging and AOA

Three sets of measurements were taken to establish a baseline for later tests to be compared against. The goal was to measure the DUT's ranging and AOA performance in all directions at different distances. To ensure unobstructed signal propagation the DUT and tag were placed at a height of 1.5 meters and with at least 1.5 meters of empty space around the devices and the direct signal path between them, see figure 20 for reference.

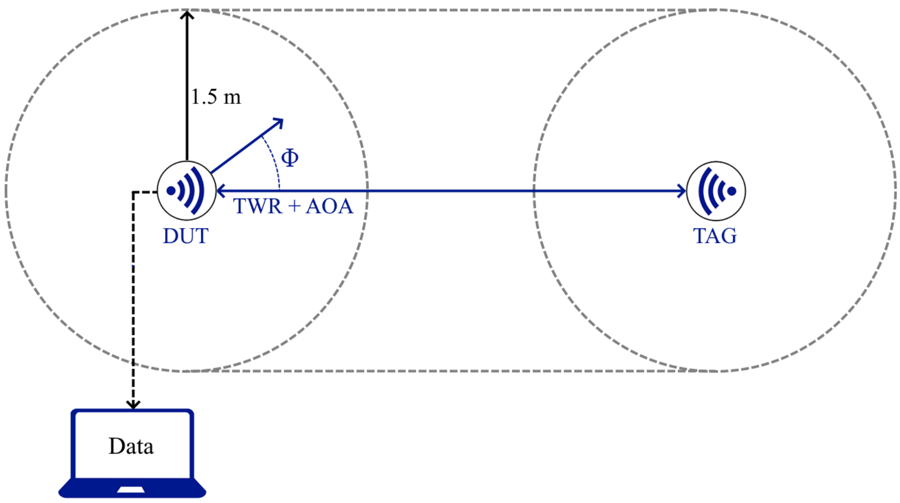


Figure 20: For the baseline measurements a minimum of 1.5 meters of empty space around the devices and the signal path between them was required.

Individual measurements were taken at 15° increments throughout the whole 360° range on the azimuth axis, from here on the reference axis is the azimuth unless noted otherwise. At each angle increment, at least a hundred data points were recorded with the UWB kit's software, the data containing both ranging and AOA information. The measurements were repeated at 2 m, 5 m, and 10 m distances from the tag.

The measurements were performed in an indoor space with other wireless devices present in the vicinity, which is expected from the typical operating environment of UWB positioning systems. Based on these measurements the DUT was determined to have a usable angle range of around ± 60°, this was the range that the rest of the measurements were be focused on, the azimuth step size was adjusted from 15° to 10° after this point. The performance across all distances was also so similar that a range of 2 meters was chosen for the rest of the measurements. The reasoning for these adjustments is discussed more in the end section 5.1.1.

4.3 Testing different enclosure materials

In a scenario where an UWB device is embedded in furniture, its antennas would be closely surrounded by different materials, a set of measurements was designed to roughly simulate the effects these conditions could potentially have on the positioning capabilities of the DUT. The tests were done by mounting a sheet of some material in front of or behind the antenna at different distances and measuring the range and AOA. A mounting bracket was 3D printed for this purpose with several slots so that the test material could be installed in front of and behind the antenna, at a distance between 3 mm to 53 mm with 10 mm intervals.[2] The materials that were chosen for these tests were: polycarbonate, plywood, glass, steel and aluminum.

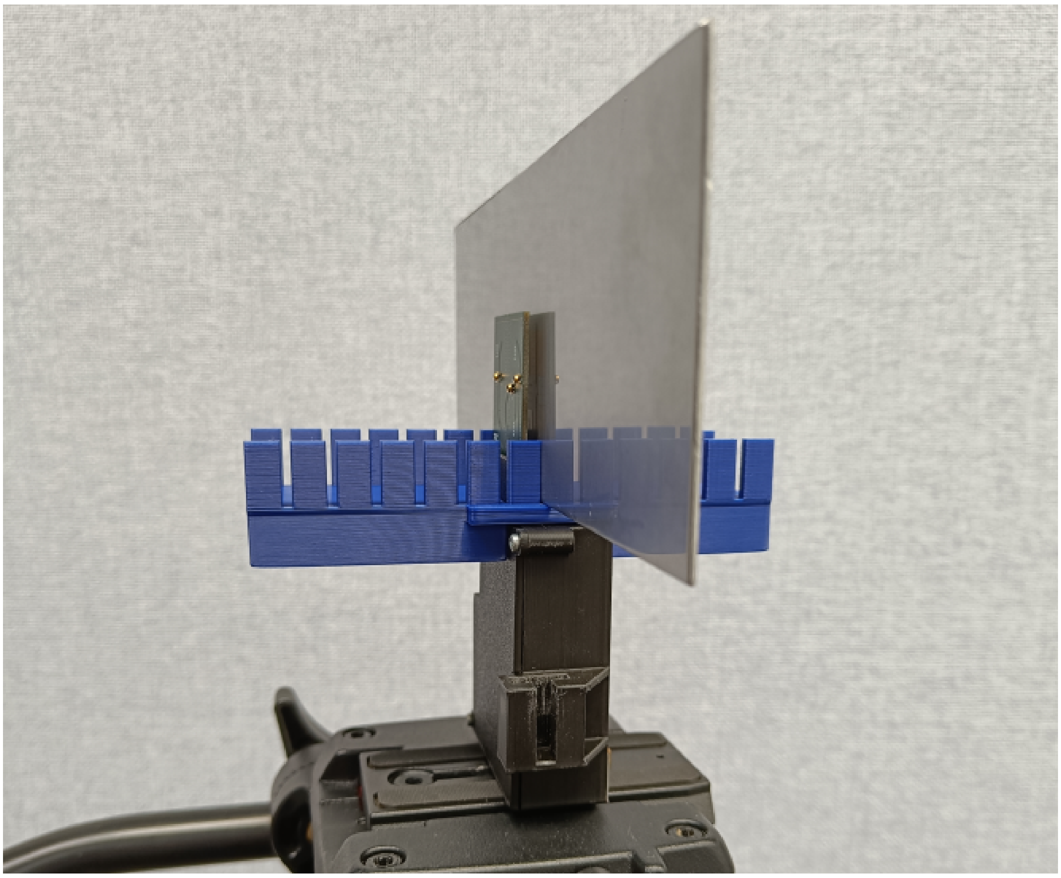


Figure 21: The mounting bracket has six slots both in front of and behind the antenna board, the slots are at 10 mm interval from 3 mm to 53 mm. In this picture a stainless steel sheet is installed in the closest position in front of the antenna board.

[2] A minimum clearance of 3 mm between the test material and the antenna board was deemed sufficient to avoid accidental shorting of the patches or connectors on the antenna board.

To keep the measurements and their results simple, flat sheets of the same size were used for these measurements, even though in the real world the shape and size of the surrounding materials wouldn't be as predictable. The sheets had to have a sufficient area so that the DUT's antennas would be blocked by the sheet across the full $\pm 60°$ range. A picture of this setup with a stainless steel sheet installed at a 3 mm distance on the front of the antenna is presented in figure 21. The dimensions of all sheets were the same: 230 mm $\times$ 80 mm $\times$ 2mm, with the exception of plywood being around 4 mm in thickness. The individual measurements that were performed are described in the following subsections.

The measurements were performed in a similar way to the baseline measurements, with the adjusted angle range and measurement increments. The results were measured on the $\pm 60°$ range with 10° intervals, the material was moved one position further away from the DUT as each set was completed. AOA and TWR data was gathered for the full angle range at all possible positions of the test material, totaling six measurement sets on both sides of the DUT for each material. There was a possibility of testing the effect of multiple materials at once in front of and behind the antenna, but in the interests of time and to keep the amount of data manageable it was decided to focus on one sheet of material at a time. In addition to the $\pm 60°$ sweep a single 360° sweep was performed with a steel sheet placed in the closest position behind the antenna, as it was deemed interesting to see whether signals originating from behind the antenna could be blocked.

5 RESULTS AND DISCUSSION

The factors that govern the placement of antennas in an UWB positioning system can be roughly divided into two categories: those that arise from the implementation of the technology itself and those that are the result of the operating environment of such systems. The former was for the most part covered by the literature research portion and the latter was experimentally tested, the results of this research are presented and analyzed in this chapter

5.1 Analyzing the measured baseline performance

The measurement campaign included a set of baseline measurements in free space conditions and a set of measurements with different materials in the immediate vicinity of the DUT's antennas which were used to perform a comparative study of the systems performance in different conditions.

5.1.1 Ranging baseline

The baseline TWR measurements from 2 meters away are presented in figure 22, all the measured data points are presented by blue dots, their mean value at each measurement point by the red markers, the actual range between the DUT and tag is represented by the green horizontal line. As discussed in chapter 4, after a preliminary analysis of the baseline results, the measurement range was adjusted to $\pm 60°$ and the measurement increment to $10°$. The baseline measurement was repeated with those adjustments for easier comparisons with later tests, figure 22 is a composite of those two measurement sets: a $360°$ sweep with with $15°$ increments (appendix A) and a $\pm 60°$ sweep with $10°$ increments. While the baseline measurements were performed from 2 m, 5 m, and 10 m distances, the performance was found to be very similar with only a slight increase in deviation from the expected values. The performance of TWR was so similar regardless of the distance between the DUT and the tag, so in the interests of time and due to spatial constraints in the test site, it was decided to perform the rest of the measurements from a range of 2 meters.

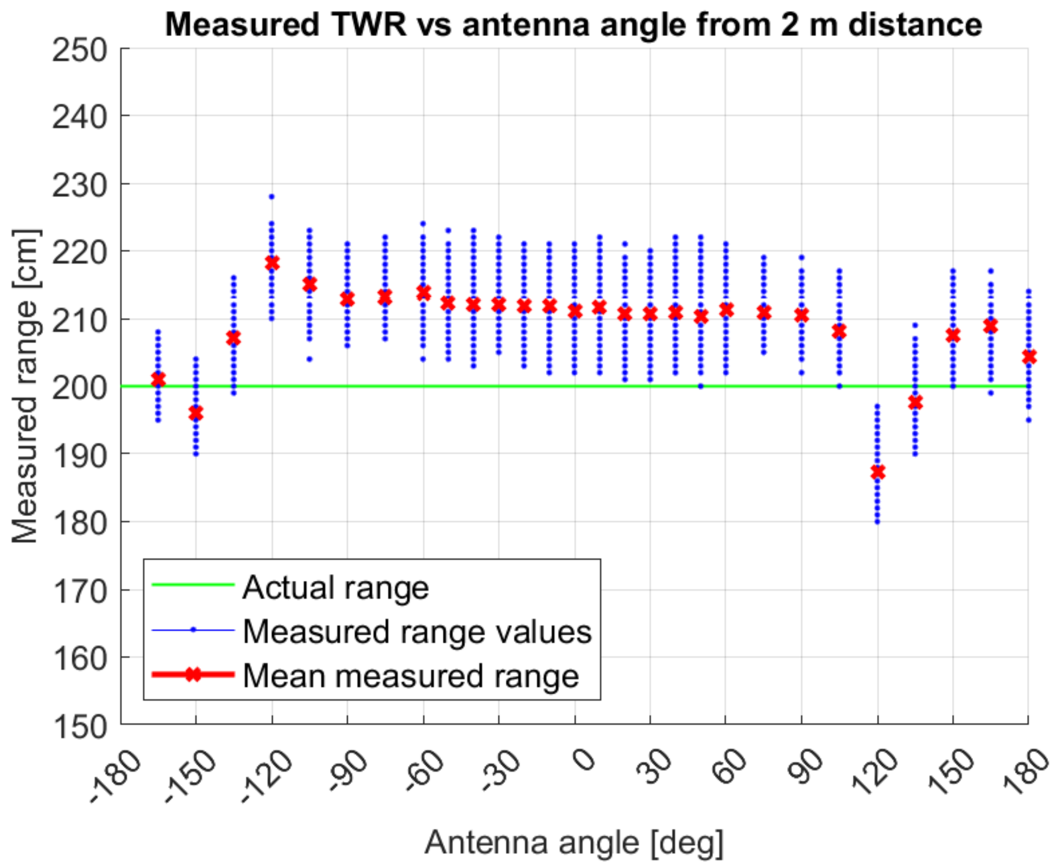


Figure 22: Measured baseline range values (blue), their averages (red) and the actual range between devices (green) at different antenna angles.

From figure 22 it can be seen that the DUT exhibits very similar ranging performance while the front side of the DUT is pointed at the tag. The average deviation from the actual range, remains at a fairly constant amount of roughly 10 cm to 15 cm above the expected value. The magnitude of the error seems to slightly increase when rotating in the negative direction. When the antenna's angle exceeds ±90° and the backside of the antenna board faces the tag the measured range becomes much more unpredictable, even dropping below the expected range right after around ±120° to ±130°. The variance of individual range measurements doesn't seem to significantly change at most measurement points, it remains at around ±15 cm.

Interestingly the average range measurements are closer to the actual range with the backside of the DUT turned towards the tag. This may be due to the electrical properties and tuning of the antenna, which is hard to prove with the available equipment. If the electrical explanation is excluded, another possibility is the signal being picked up at a point closer to the chip on the on-board signal path. While the TWR reference antenna gets slightly closer or further away from the tag as the DUT is turned because it is slightly offset from the axis of rotation, it wouldn't fully explain this behavior. The average range measurement drops regardless of the direction of rotation, this would only happen if the antenna got closer to the tag, which isn't the case here. As mentioned before, the TWR reference antenna is ANT3, illustrated in figure 17, it gets slightly further away from the tag when the DUT is rotated in the positive direction, which should increase the measured range, not decrease it. There is a possibility that, when the DUT's backside is facing towards the tag, the signal is picked up by the antenna connectors and/or traces on that side of the board, see the right side of figure 17. This would make the signal path on the board itself shorter, which would result in a shorter measured TOF and therefore shorter range.

5.1.2 Baseline angle of arrival

The results from the AOA side are presented in figure 23, in a similar fashion to the TWR results. All data points are presented by blue dots, their averages with red markers and the expected AOA measurement with the green line. The included software doesn't support angles of over ±90° so the AOA measurement saturates[1] at some DUT angles, these instances are highlighted by magenta markers. The AOA performance was also found to be similar at different distances, similar to TWR.

The key takeaway from figure 23, is that the AOA measurement has decent accuracy in the ±60° range, only deviating from the expected value by a few degrees on average with very little variance. When going beyond that range the AOA saturates to -90° in the negative direction. After the DUT antenna angle exceeds ±90°, the AOA starts to drift in the opposite direction. ±90° is the maximum range of the software and the DUT has no way of knowing whether the signal is coming from the front or backside of the board, when it is rotated so that the backside points at the tag the angle measurement just flips. A lot more variance can be observed from the backside, probably because the on board signal path isn't as well defined in this scenario. While the software itself is configured to measure AOA between ±90°, the manufacturer apparently has calibrated the board for ±60° (Mobile Knowledge, 2023a).

[1] A measurement where all measured AOA values are either only 90° or -90°.

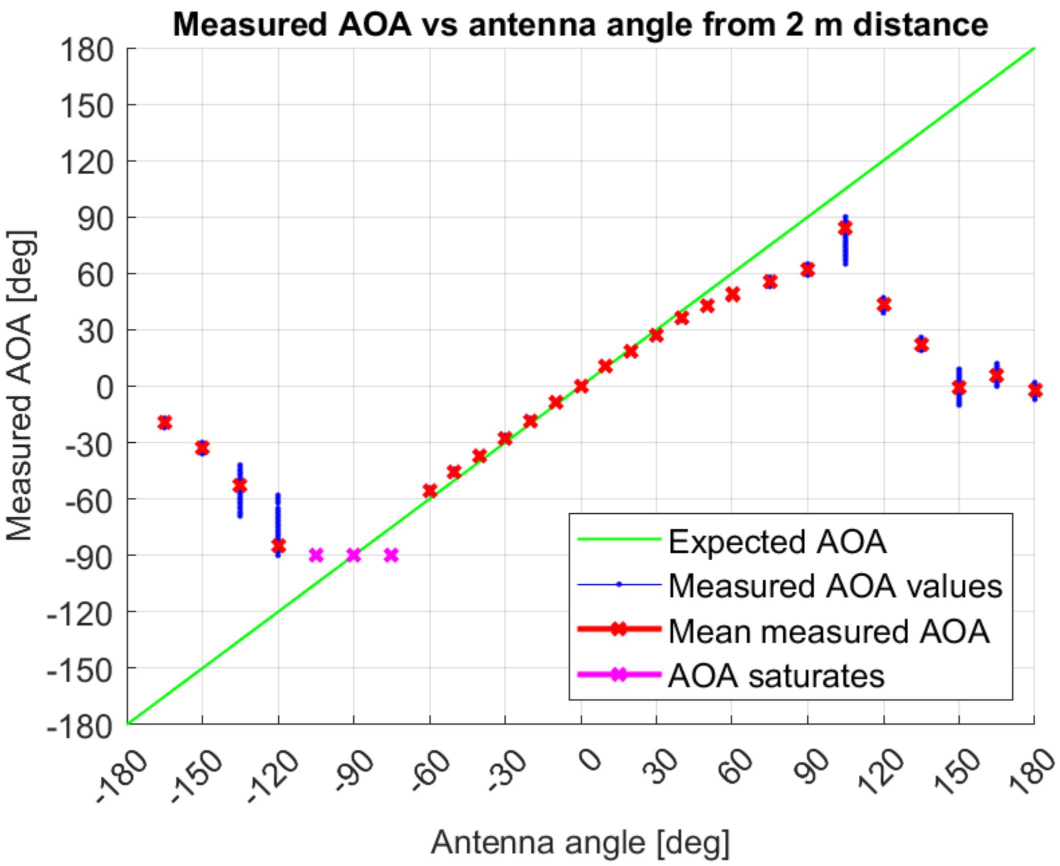


Figure 23: Measured baseline AOA values (blue), their averages (red) against the actual antenna angle (green). At some points the AOA measurement saturates to -90° (magenta).

With those factors in mind it was decided to limit the rest of the measurement campaign to the "usable range" of ±60°, where the AOA best aligns with the expected angle. The measurement interval was adjusted to 10° instead of 15° to get more data points within this range. Some later tests were performed outside the usable range if deemed interesting. Nevertheless the DUT was able to successfully measure range and AOA for the whole 360° range. This means that for real world applications the possibility of false positives from behind an antenna array should be addressed to avoid unwanted behavior.

5.2 Analyzing the effect of different materials

The first step of these tests was to determine whether attaching the mounting bracket of figure 21 affects the baseline performance by itself. The average deviation from the ideal values for both AOA and TWR, measured with and without the bracket, are presented in figure 24. These graphs are formed by subtracting the actual angle and range values from the measured values. The blue lines represent the baseline measurements from section 5.1.1 and the red lines represent the same measurement with the mounting bracket installed. In an ideal scenario, the measured AOA and TWR would match the actual antenna angle or distance exactly, which would just form a straight horizontal line at zero degrees/centimeters for both measurements.

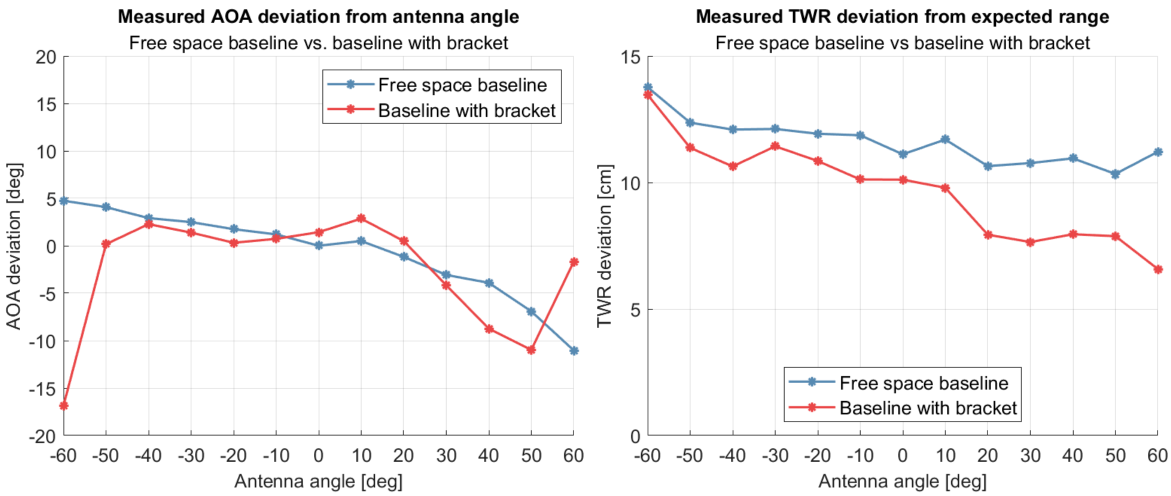
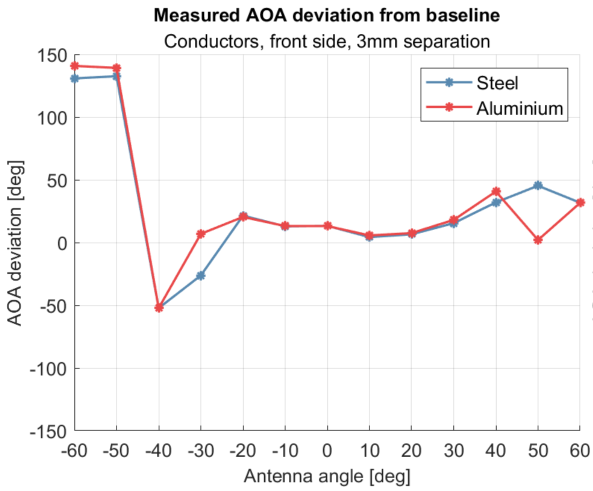


Figure 24: AOA deviation from actual antenna angle (left) and TWR deviation from actual distance (right) for both with and without the mounting bracket.

Looking at figure 24, the mounting bracket obviously has a significant effect on the DUT's performance. At around -40° to 30° the AOA measurement (left) roughly follows the original baseline graph but starts to drift away at opposite directions at the edges of the measurement range. The TWR measurement (right) is also off from the original baseline, with almost no deviation at -60° and the gap gradually widening to around 4 cm at 60°. The range is measured to be shorter on average with the bracket installed, which brings it closer to the ideal value. The results with the mounting bracket installed was used the baseline for the rest of the measurements. To clarify: figures 25, 26, 27, 28, 29, 30 as well as appendices B, C, D and E all represent the measured deviation from the AOA and TWR results presented in figure 24.

5.2.1 Conductors: steel and aluminium

The materials that were tested can be divided into conductors and insulators, the former's results are analyzed here and the latter's in the next section. Displaying the full results would up a lot of space so they are not included here, they can be found in appendix B for AOA and appendix C for TWR. The following figures represent the average deviation from the baseline measurement, with the mounting bracket installed, which was presented in figure 24.



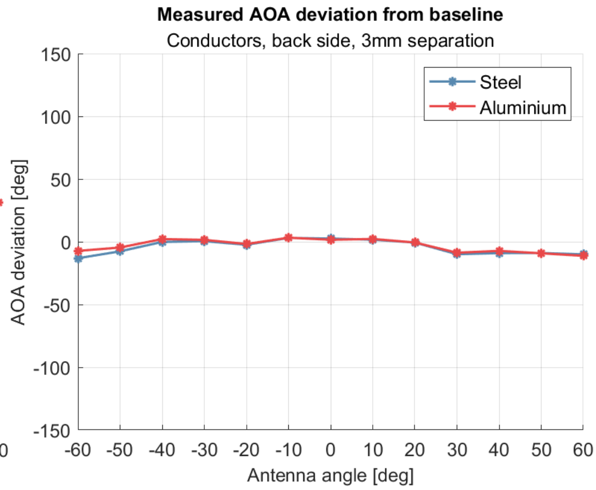


Figure 25: AOA deviation from baseline with steel and aluminium sheets installed at a 3 mm distance on the front (left) and behind (right) of the DUT.

The results for AOA with steel and aluminium installed in front of and behind the DUT at a 3 mm distance are presented in figure 25. For the most part the results for steel and aluminium very closely match each other with some outliers at specific angles. The presence of metal in front of the antenna results in deviations of up to around 140° at the worst, the magnitude and direction of these errors often changes but there is a pattern. The magnitude of the deviation in AOA seems to change periodically depending on the DUT's angle, when looking at the full set of results a clear pattern of peaks and valleys can be seen. Additionally their density, and the angles at which they appear, change depending on the separation between the sheet metal and the DUT. Similar behavior can be observed when the metals are installed behind the DUT, although the magnitude of error is on average less than with the sheet installed at the front. In both scenarios the largest swings happen at the edges of the angle measurement range.

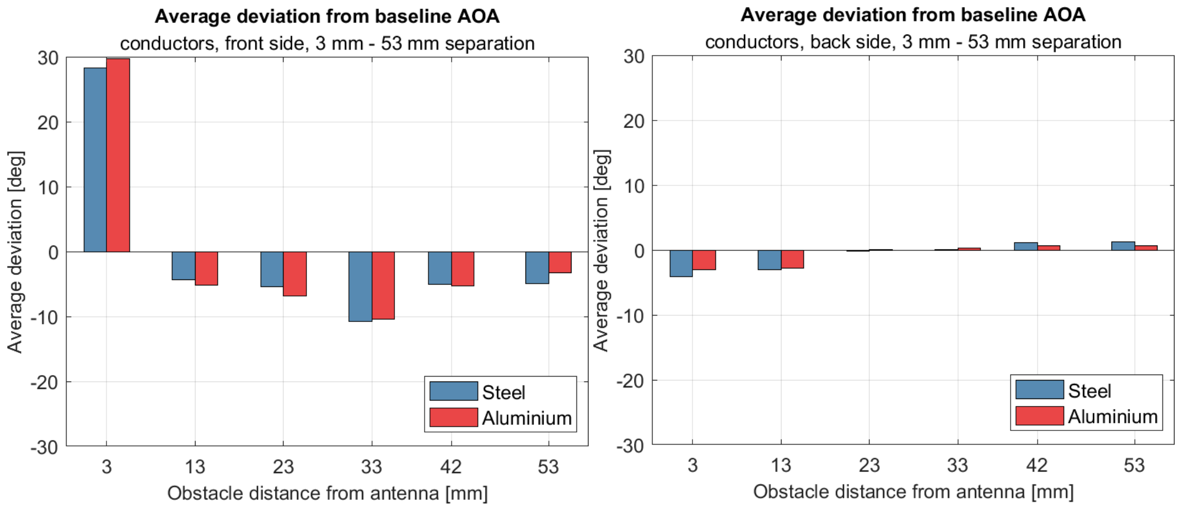


Figure 26: Average AOA deviation from baseline with steel/aluminium, installed at different distances, on the front side (left) and behind (right) the DUT.

The average AOA deviation at different distances from DUT to test material, meaning the average deviation across the whole ±60° sweep at each position of the metal sheets, is presented in figure 26. The distance between the materials and the DUT is displayed on the x-axis and the average deviation from the baseline on the y-axis. The results for when the material is in front of the DUT are on the left and on the right are the results for the back side. A good number of interesting characteristics can be observed in these results. For the front side the average deviation is three times larger in the closest position (3 mm) than at any other point, though the exceptionally large deviation of 140° at -50° and -60° in this position is partially to blame for this. What is particularly interesting is that the 3 mm position is the only position on the front side where the average deviation is positive, after that it increases gradually, reaching a maximum of around -10° at 33 mm and then, decreasing for the rest of the way. On the other hand, when one of the sheets is installed behind the antenna the deviation is negative at first in the 3 mm and 13 mm positions, virtually zero at 23 mm and 33 mm, and then flipping to the positive side at 42 mm and 53 mm.

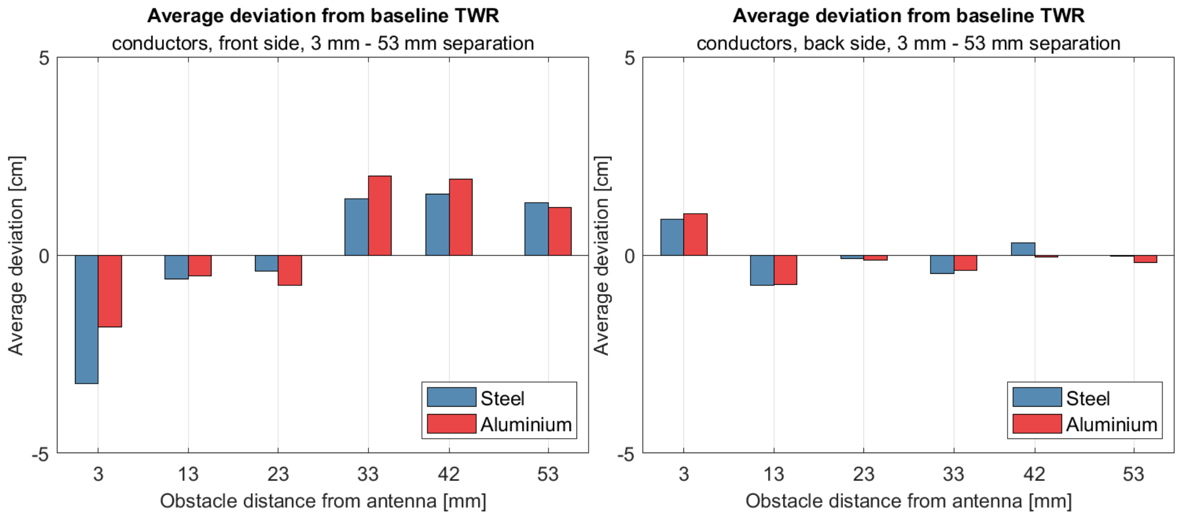


Figure 27: Average TWR deviation from baseline with steel/aluminium, installed at different distances, on the front side (left) and behind (right) the DUT.

The average deviation from baseline for TWR is presented in figure 27. The bars represent the average deviation for the whole angle sweep at different distances to the metal sheet being tested, on the left are the results when the material was in front of the DUT and on the right are the results for materials behind the DUT. The full TWR results for aluminium and steel can be found in appendix C. When installed on the front side, the metals clearly have an effect on the measurements, with average deviations ranging from little over -3 cm to 2 cm. The performance was generally somewhat uniform across the full angle range, with some outliers at the 3 mm and 13 mm positions. On average however, the ranging performance is affected to a much lesser degree than AOA, an average deviation of just a few centimeters should be accurate enough for most applications. When the materials are installed behind the DUT the effect is mostly negligible, aside from slightly higher deviation at high angles at the closest test sheet position of 3 mm.

5.2.2 Insulators: glass, polycarbonate and plywood

The average deviation from baseline results for a $\pm 60°$ azimuth sweep with glass, polycarbonate and plywood, installed in front of and behind the DUT at a 13 mm distance, are presented in figure 28. The results for materials on the front side are on the left and the back side on the right. The full results once again, can be found in appendix D for AOA and appendix E for TWR.

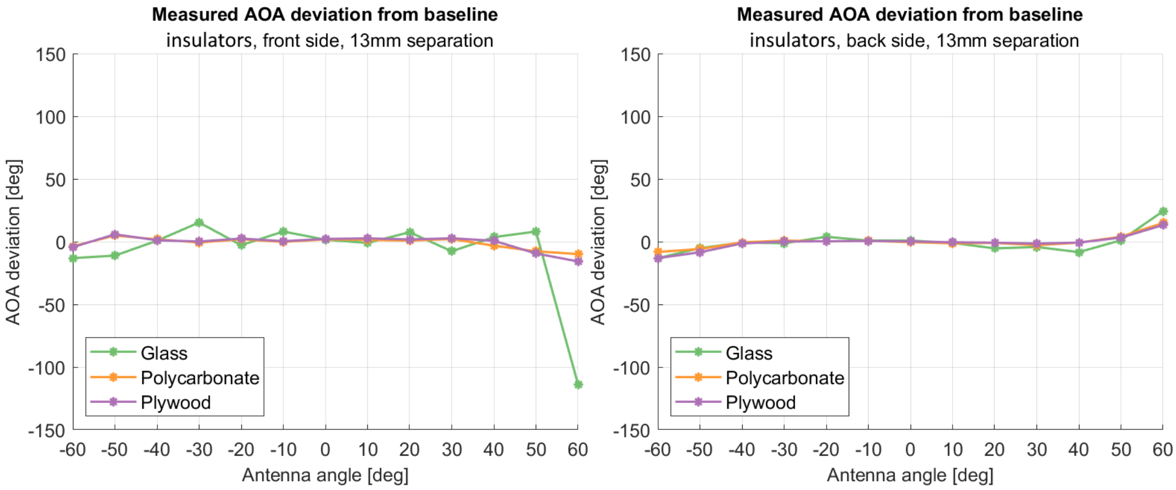


Figure 28: AOA deviation from baseline with glass, polycarbonate and plywood sheets installed in front (left) of and behind (right) the DUT at a 13 mm distance.

When comparing the the results in figure 28 against one another, it seems that polycarbonate and plywood match each other very closely, while glass causes significantly larger deviations at certain angles. The effect is best illustrated at the 13 mm position, glass seems to cause the measured deviation to change direction and magnitude at almost every angle increment. In a similar pattern to metals, the measured deviation is often at its largest at the edges of the measurement range for all tested insulators. For glass, particularly large deviations appear at 60°, this is repeated at most positions on the mounting bracket, with the largest swing reaching almost -130° when the glass is installed at the closest position in front of the DUT.

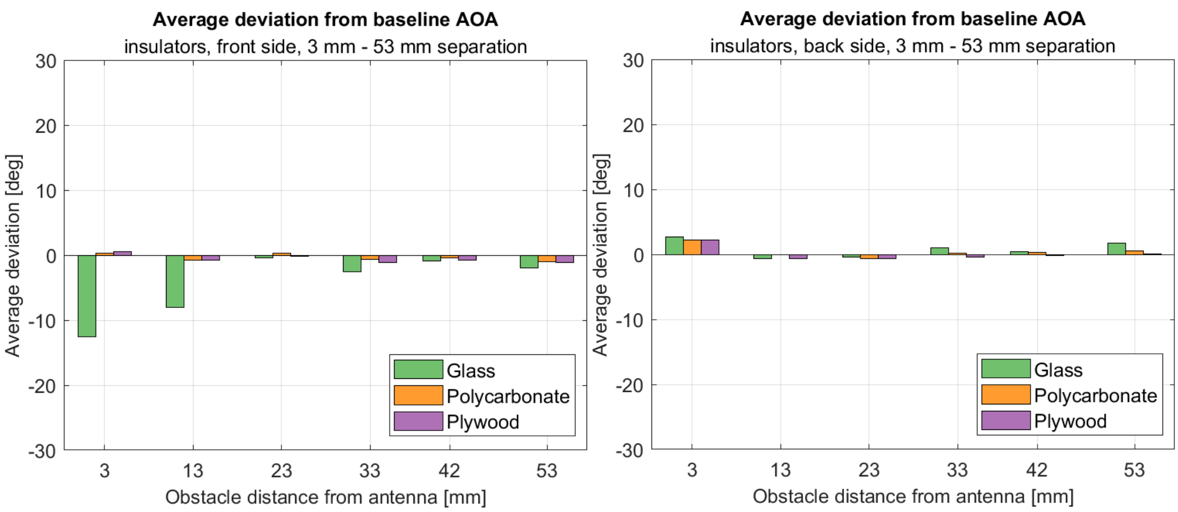


Figure 29: Average AOA deviation from baseline with glass/polycarbonate/plywood, installed at different distances, on the front side (left) and behind (right) the DUT.

The average AOA deviation across the whole angle range for the front (left) and back (right) are presented in figure 29, the distance between the materials and the DUT is displayed on the x-axis and the average deviation from the baseline on the y-axis. In a similar fashion to steel and aluminum the average deviation is at its largest in the closest positions to the DUT and after reaching a minimum at the 23 mm position it starts to slightly increase. What really sticks out here is that on average, glass causes considerably more problems for the DUT than plywood or polycarbonate.

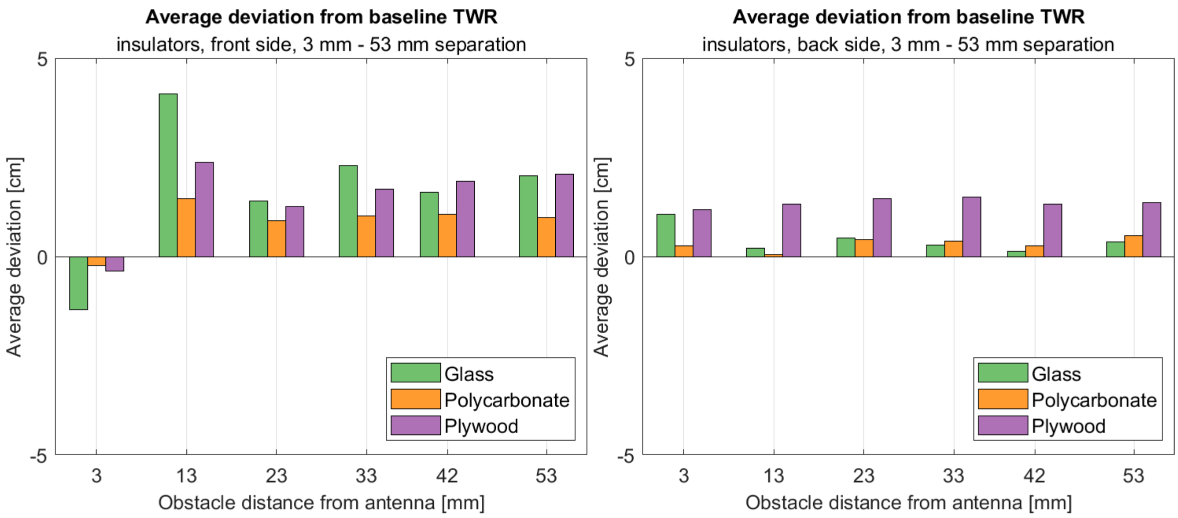


Figure 30: Average TWR deviation from baseline with glass/polycarbonate/plywood, installed at different distances, on the front side (left) and behind (right) the DUT.

The average deviation for the TWR side of the measurements with insulators are presented in figure 30. On average the presence of the three insulators adds positive deviation to the ranging measurement with the exception of the 3mm position in front of the DUT, where it is slightly negative. An interesting feature of these results is that while glass seems to be the largest source of disturbance when installed on the front side, behind the DUT plywood causes the most deviation overall, although the numbers are very small. Overall the deviation in ranging caused by these materials is not very significant, when compared to the 10 cm - 30 cm accuracy that UWB devices are commonly advertised to have.

5.2.3 Other findings

Other interesting things were discovered during preliminary testing of the measurement setup, which may be worth investigating further in the future. As was shown by the baseline measurements, the DUT has no problem measuring the range of devices behind the antenna board. Interestingly the range measurement is on average shorter at certain angles behind the DUT. It was hypothesized that the incoming signal may be picked up by the connectors on the backside of the antenna board, thus resulting in a shorter on-board signal path and a shorter range measurement. To test whether the signals from behind the board could be blocked, a 360° sweep was performed with a steel sheet installed at the 3 mm position behind the DUT. The results for TWR in this test are displayed on the left side of figure 31, the baseline is displayed on the right for reference. At angles over ±90° it seems that the shortening effect of the TWR measurement is removed by the steel sheet, also at 90° the bulk of the range measurements are clearly split into two groups.

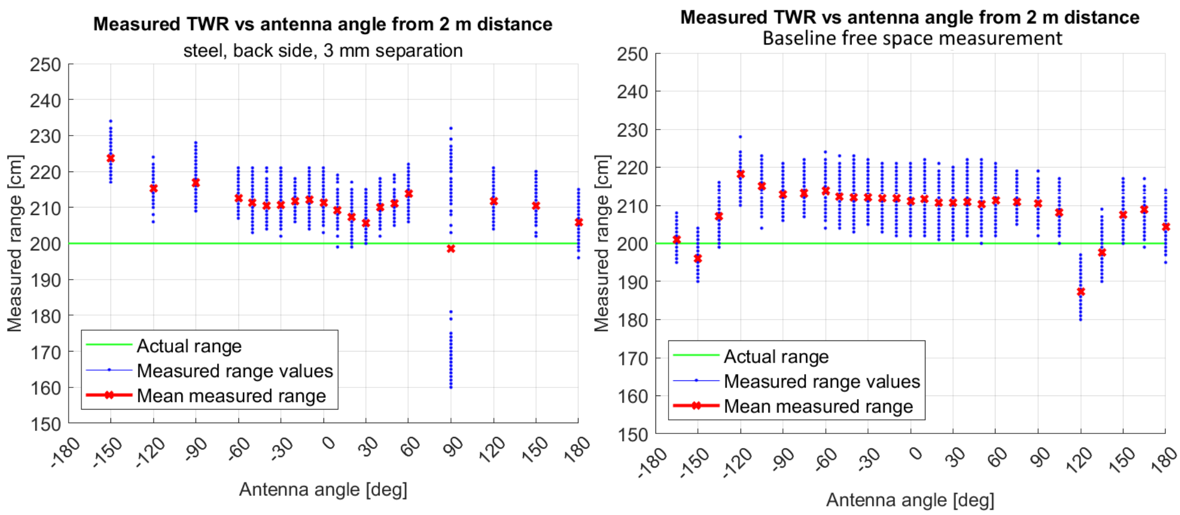


Figure 31: A full 360° TWR sweep with a steel sheet installed at a 3 mm distance behind the DUT (left) and the baseline TWR measurement results (right).

Another interesting discovery was that when a plastic sheet was placed in front of the DUT and rotated along the horizontal axis it had a clear effect on the AOA measurement. When the sheet was rotated counter clockwise it caused the AOA measurement to shift in the negative direction and the opposite when it was rotated clockwise. This means that the shape and orientation of an enclosure relative to an UWB positioning anchor's antenna can also significantly interfere with AOA measurements. This phenomenon wasn't investigated further due to time constraints.

5.2.4 Key takeaways

The overall conclusion that can be drawn from these results is that materials surrounding the DUT definitely have an effect on the accuracy of UWB positioning. These simple tests should at the very least provide insight into what factors could become issues while designing UWB positioning devices. There are a lot of variables at play here, so the exact mechanism which results in the behavior that was measured may be impossible to pinpoint based on these kinds of tests alone. The obstacles placed near the DUT may change the tuning of the antennas, interfere with the waveform of the UWB signals directly or by reflections, affect their time of flight or a combination of all of those, with some other unknown factors mixed in.

Of the tested materials steel and aluminium clearly have a much larger effect on the DUT's performance, which was expected based on intuition, since the presence of metal objects on the signal path of any wireless communication rarely helps their operation. Glass, polycarbonate and plywood also affected the DUT's performance, but the effects were typically less pronounced, especially at lower antenna angles. AOA was more sensitive to obstacles than TWR, even plastics were shown to significantly interfere with its operations. A common theme across all measurements, even at the baseline level, was that the estimation of AOA and range becomes increasingly unreliable as the angle of the DUT's antenna increases in either direction.

The overall question with these measurements is: what do the results mean in the context of developing UWB anchors and installing them within the intended operating environment. The measurements showed that, while there was little variance in individual data points within the specified range of $\pm 60°$, the overall performance can change unpredictably as the position and material of an obstacle changes. In a one-off solution these factors wouldn't be that much of a problem since the deviation could probably be compensated for in software with little effort. But therein lies the problem when the goal is to mass produce an UWB anchor, especially one that utilizes AOA measurements. Not only would a designer have to design the enclosure to fit the antennas' specification but also take into account the effect of the surrounding materials in the end use location. The anchor should therefore be designed in a way that whatever is in the immediate vicinity of the antenna, should have as little effect as possible on the anchor's performance. The environmental factors in the end location are rarely in the hands of the designer, so the solution would probably be to make the environmental factors as constant as possible in the direction of the target area and shield the antenna from interference in all other directions. On-site calibration sure is possible, but impractical for a mass produced device, especially if it is intended for the consumer market.

5.2.5 Addressing some issues

The setup used for these measurements is far from perfect. In addition to the issues raised in section 4.1.2 these tests were particularly full of potential sources of errors and uncertainty. First of all, the dimensions of the test materials and the way they are positioned is less than ideal. The sheets block the direct signal path to the antenna but there's no telling what happens at the edges of the sheets and how much of a role does the size of the obstacle play in the results. The results may be very specific to obstacles of exactly 230 mm $\times$ 80 mm $\times$ 2mm in size and may be vastly different if the dimensions were doubled for example.

Secondly the possibility of human error in these measurement sets was high. The measurements required a lot of manual adjustments to the setup and handling of output files. Also these measurements required a large amount of repetitions, so it's very possible that some mistakes were made at some point of the process. And depending on where in the chain a mistake happened it may be anything between obvious to impossible to distinguish from legitimate results. There were some instances where one position on the mounting bracket was accidentally skipped, those were relatively easy to catch. The measurements were always performed in the same order and the output files were always similarly labeled to alleviate some of these issues but it's entirely possible that some mistakes made it through to the final version of the results.

5.3 Thoughts on product development with IEEE 802.15.4z positioning

In this section the features of each positioning technique described in 802.15.4z are explored from the perspective of actually designing a small form factor UWB positioning anchor. The different requirements for TWR, TDOA and AOA each have their on effect on the form factor and deployment intensity of a product utilizing one or more of these techniques. The regional regulations are also an ever-present factor, so the compatibility of 802.15.4z (Amendment 1) and ETSI EN 302 065-2 V2.1.1 is briefly discussed here.

5.3.1 Form factor and deployment intensity

When a small form factor is desired for a positioning anchor so that it can easily be embedded into furniture et cetera, the available UWB solutions depend on how this requirement is interpreted. Designing an individual, one-antenna anchor device in a small enough package is relatively trivial. A single MPA does not require much space, especially on higher frequency channels, so the issue is more one of positioning the anchor devices themselves. So, if having external anchors in addition to the host device is accepted there isn't really any issue in using whatever positioning technique. However, if the goal is a single monolithic device, that is still capable of positioning, the options become much more limited.

As discussed in chapter 3, TWR and TDOA based positioning systems require at least 3 anchors with spacing of several meters between them and the anchors must fully envelop the target area. This property of TWR and TDOA makes designing a monolithic positioning anchor near impossible. An AOA based positioning anchor should be able to fit in a smaller package, provided that it has at least two AOA nodes with some spacing between them, however there isn't much material available on this kind of solution. On the other hand, a device that utilizes a combination of TWR and AOA to achieve positioning capability seems more approachable, for example this is what the "3D Antenna Board" does. And the measurements show that this kind of solution can achieve very good positioning accuracy on a 2D plane, with the right conditions.

Another factor worth considering is the deployment intensity of these devices, meaning how much effort is required to get the positioning system up and running. Ideally a positioning system would be able to be deployed on a plug-and-play basis, especially if the device is intended to be installed by a non-professional end user. In a general terms, TDOA and TWR based solutions fall short in this regard, since the installation process includes recording the relative locations of each anchor and calibrating the system accordingly, whether this process could be automated wasn't investigated in the research material. Once again a combination of TWR and AOA seems to be the easiest solution, in principle this kind of device could be very quickly be installed by anyone, and depending on the use case it may not even be required to have access to its own location within its target environment.

5.3.2 Compatibility with EU regulations

When developing a wireless product of any kind for the global market, the regional restrictions on such technologies are a critical issue. Since UWB devices are generally based on 802.15.4z (Amendment 1) a good starting point is verifying to what extent that standard is complying with local regulations, in this case the before mentioned ETSI EN 302 065-2 V2.1.1 standard, which is based on EU directive 2014/53/EU.

Generally the frequency bands defined in Amendment 1 overlap with the ETSI bands with a couple notable exceptions, which is expected since the EU regulations predate the IEEE standards. For indoor operation the allowed frequency band is the LT1 range of 6 GHz to 9 GHz[2], this covers most of the LRP PHY and the high-band of HRP PHY, leaving low-band HRP PHY outside the allowed range. For LT2 type systems the only option is the 3.1 to 4.8 GHz low band HRP PHY which matches exactly with the LT2 specification. The relationship between these frequency bands is illustrated in figure 32, allowed range is highlighted in green, prohibited band in red. In terms of available channels this restriction leaves channels 12 to 15 of the high-band HRP PHY unavailable for indoor positioning as well as channels 3, 7, 8 and 9 for the LRP PHY.

[2] 6 GHz to 8.5 GHz without DAA active mitigation.

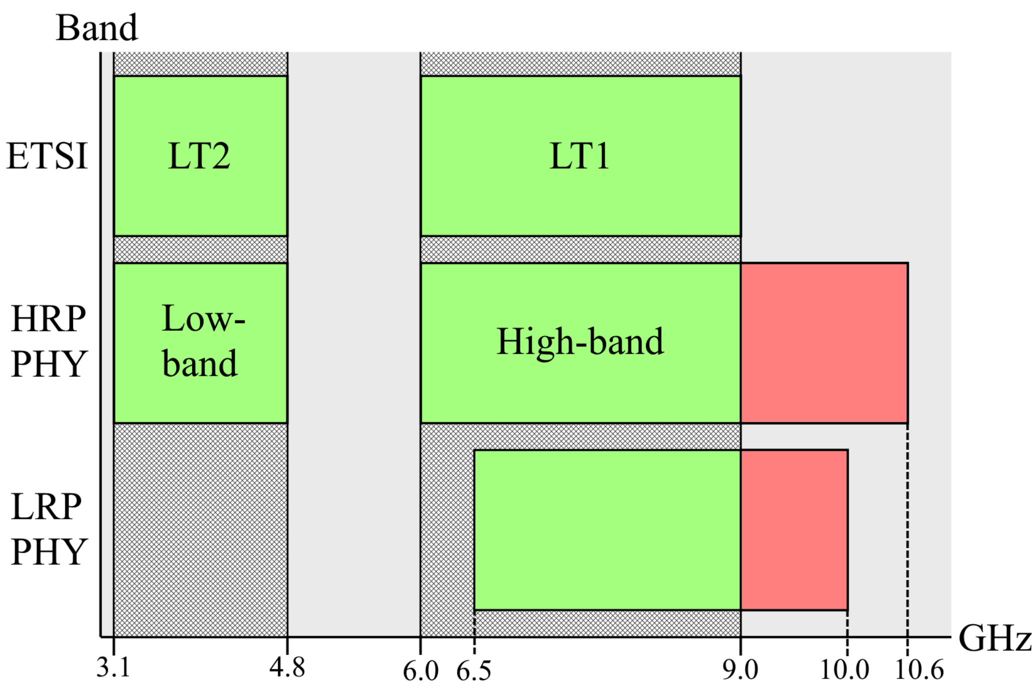


Figure 32: The compatibility between ETSI EN 302 065-2 V2.1.1 positioning frequency bands (LT1 and LT2) and 802.15.4z bands (high/low -band HRP PHY and LRP PHY).

So the EU Directive 2014/53/EU prohibits the use of some of the UWB channels of Amendment 1 for indoor positioning applications, but what about the applicability of the different positioning methods? When only operating indoors, in general anything goes, provided that it conforms to the LT1 emission limits. If one wanted to make fixed UWB tracking anchors that can be installed both indoors and outdoors and not be subject to licensing and registration there is one major restriction on the possible positioning techniques. As was discussed in section 2.1.1, LT1 -type positioning systems are prohibited from having fixed transmitters outdoors, though it's implied that receivers would be allowed. Therefore, the only legal way of implementing an outdoor positioning system would be one whose anchors operate on a receive only basis. This basically means that the only currently available Amendment 1 -compatible option would be a TDOA based system with wired clock synchronization. Which in turn means that, due to the nature of the technique it would be impossible to have it be a single small form factor device, not at least without some novel solution. Another possible solution is a system based on only AOA, since it's based on TDOA and doesn't require two-way communication. At a glance there doesn't seem to be any available systems that use AOA this way, TDOA is way more popular, more research would be needed to obtain a better understanding whether this kind of approach would be practical. An additional noteworthy consequence of these regulations directly affects antenna placement for AOA applications.

The optimal separation between antennas gets smaller as the channel frequency increases, and since the ETSI limits cut off some of the higher frequency channels, the antenna array for AOA can't be as compact as it could potentially be without these limits.

As a reminder and a disclaimer it should be noted that these conclusions are inferred from a very brief regulatory review that specifically targeted UWB positioning applications within the EU and may not, nor is it intended to, paint a complete picture of the legal status of UWB. This section and section 2.1.1 are based on the assumption that ETSI EN 302 065-2 V2.1.1 would be the standard that a commercial UWB positioning system would be operating under in the EU. This standard is meant to "provide one voluntary means of conforming to the essential requirements of Directive 2014/53/EU" (ETSI, 2016). A more thorough analysis should be conducted before engaging in serious design work.

6 CONCLUSIONS

The goal of this master's thesis was to obtain information on the main factors that affect the mechanical dimensions and placement of antennas in ultra-wideband (UWB) indoor positioning systems. A literature review was performed of the standard positioning methods that are currently used in commercial UWB positioning systems and the EU regulations that govern the usage of such systems. The goal was to obtain preliminary information on the operating principles of common UWB positioning techniques and how do they relate to the mechanical dimensions of the antennas of an UWB positioning system and their placement. UWB positioning often involves a set of fixed transmitters with known locations in space, which are called "anchors", that are used to track the location of a mobile target device, the focus of this thesis was on the anchors specifically.

A test setup was designed and built to test the performance of an UWB development kit. The main goal of the tests was to obtain experimental data on how do different materials that are commonly encountered in an indoor environment affect the accuracy of the positioning anchor, when they are placed in the immediate vicinity of the anchor's antennas. The performance of the anchor was examined by conducting comparative analysis of a known baseline measurement in free space conditions against results with different materials near the anchor.

Overall the literature review succeeded in obtaining an understanding of what a designer working on an UWB positioning project could expect in terms of the antenna(s) and the available solutions for such systems. Different positioning techniques were found to each have their own unique set of rules on the dimensions and placement of positioning antennas. Additionally the regional regulations were also found to impose limits on the available solutions. The measurement campaign was successful in roughly simulating an UWB positioning anchor being embedded in furniture, although the applicability of the measurement results in a broader context could be called into question. The main findings of the literature review and the measurement campaign, as well as suggestions for future research are presented in the following sections.

6.1 Antennas and their placement

Three main factors that define the rules for the placement of UWB antennas for positioning purposes were identified. They were, in order of descending importance: the chosen positioning method(s), the surrounding materials and EU regulations. The dimensions of UWB antennas were also deemed to be a significant factor in the design process of UWB positioning devices however, in the broader context of designing a whole device, the shape and size of a single antenna seemed to be a relatively trivial issue.

6.1.1 Positioning methods & antenna dimensions

When designing an UWB positioning system, one of the first questions that one would face is the choice of the positioning method(s) that the system would operate on. There are three basic positioning[1] methods defined in IEEE 802.15.4z, which forms the foundations for modern UWB devices. All positioning methods have their own rules for optimal antenna placement and the amount of antennas required. Two-way ranging (TWR) can use a single antenna to determine the distance to its target, which is relatively low in design complexity. For finding the position of a target, at least three independent antennas are required, it was determined that each node would have to be separated from each other by several meters. Time-difference of arrival (TDOA) needs at least three antennas to achieve positioning, a single antenna can't be used for ranging. TDOA suffers from a similar problem to TWR, the antennas must fully envelop the target area, which means they also have to be placed far apart from each other. Angle of arrival (AOA) needs two antennas to determine the angle at which a signal was received, the optimal separation of those antennas is exactly half of the wavelength of the UWB channel being used. A single AOA node can't be used to determine the range between devices, so it's often used together with TWR to determine the distance and direction of a target. A two antenna system using a combination of AOA and TWR seemed to be the most compact positioning solution.

There are many different antenna types that have been used for UWB applications, the focus of this thesis was on the microstrip patch antenna (MPA), since it seems to be one of the most popular antenna types in modern UWB devices and the type that was used by the development kit chosen for the measurements. MPAs are easy to manufacture and prototype, since they can be directly etched onto a circuit board. In its most basic form an MPA is just a rectangular patch connected to a transceiver with a feed line. The shape and size of the patch and the feed line is determined by the intended operating channel(s), the higher the frequency the smaller the patch. Generally in UWB applications, one could expect a single MPA to be around the size of a fingernail, with some empty space reserved around it.

[1]Positioning in this context means finding the location of a mobile target on a 2D plane, 3D positioning is a subject for another thesis entirely.

6.1.2 The effect of surrounding materials

A development kit capable of TWR and AOA ("MK UWB Kit SR150/SR040") was used to test the effect of different materials in the immediate vicinity of its antennas, with the goal of roughly simulating the device being embedded in furniture. The tested materials were steel, aluminium, glass, polycarbonate and plywood. The effect every one of the materials had on the TWR and AOA performance was tested with a sheet of material installed in front of or behind of the antennas. AOA was clearly the more sensitive procedure, all materials had a significant effect on its performance at some point of the measurement range, both in front of and behind the antenna. TWR on the other hand, turned out to be more robust to obstacles around the antenna than was initially expected, within the measurement range at least. A definitive answer as to why each material had the effect it did wasn't possible to ascertain based on this research. What matters in the broader context is that the geometry of the enclosure of an UWB positioning anchor matters, sometimes by a lot. Therefore, the enclosure of any UWB device should be designed to fit the antenna specifications, not as an afterthought. And not only should the enclosure not interfere too much with the antenna, the installation environment should also be taken into account and it's effect should be minimized when possible, to reduce the need of on-site calibration of positioning products.

6.1.3 Standards & regulations

As is the case with all wireless communication, the operating frequency range and transmission power of UWB are regulated by governmental bodies. The UWB range is defined in the EU to be from 3.1 GHz to 10.6 GHz however, indoor positioning systems are limited to a narrower band of 6.0 GHz to 9.0 GHz, these are referred to as "LT1" type systems by ETSI. Outdoor positioning systems on the other hand are allowed to operate between 3.1 GHz to 4.8 GHz, these are known as "LT2" type systems and are subject to licensing and registration. The IEEE standard 802.15.4z includes UWB channels within the ranges of 3.1 GHz to 4.8 GHz and 6.0 GHz to 10.6 GHz. Which means that a good number of available channels are unavailable for the standard forms of UWB positioning. This means that the separation of AOA antennas, which is directly defined by the channel frequency, is limited by regulation to be at minimum wider than the 802.15.4z standard is capable of. The EU regulations also limit the available positioning methods when operating outdoors, fixed LT1 type outdoor UWB transmitters are prohibited, which means that positioning methods that require bidirectional communication, such as TWR aren't allowed outdoors if it's connected to fixed infrastructure.

6.2 Suggestions for future work

There were a number of things that could not be tested due to time- and equipment constraints, as well as some open questions left from the literature research. The major questions and ideas for potential future research are presented below.

6.2.1 Testing with different antennas

The “MK UWB Kit SR150/SR040” provides a good starting point for testing the full functionality of the included chips and developing software solutions for them. However, as a development kit it’s designed precisely for that purpose, function before form. For testing the factors that affect antenna placement and enclosure design it is a less ideal tool. For example the unshielded antenna traces and connectors on the backside of the “3D Antenna Board” raised some questions on the real world applicability of the tests performed in this thesis, since they were found to have some effect on the results whether they were blocked or left exposed.

A natural continuation from the testing performed with the ”3D Antenna Board” would therefore be to test its TWR and AOA functionality with different external antennas, for which the board already has connectors available. A particularly interesting alternative to the on-board MPA solution would be to test the much smaller surface mounted chip antennas, the likes of which can be found on the tag in figure 19, for example. These kind of antennas take much less space on a PCB compared to patch type antenna, and would potentially be a more flexible solution for small scale applications.

It’s unclear how much of the gathered data is applicable on a broader scale and not just the specific measurement setup used in this thesis. It would be beneficial to measure the radiation pattern and other related performance metrics of the ”3D Antenna Board” to add another dimension to the measurements and in doing so hopefully provide better insight to the results.

6.2.2 Other positioning methods & 3D positioning

The only positioning method that was tested in practice was a single anchor using a combination of TWR and AOA, TDOA based positioning couldn’t be tested at all. In the future the scope of testing could be extended to multi-anchor positioning systems based on TWR and/or TDOA to see how easily those kinds of systems are affected by their environment. Another interesting possibility would be to try triangulation with multiple AOA anchors. Most of the literature is focused on positioning on a 2D plane, there’s not much information available of applying 3D positioning in practice, this possibility should be investigated further.

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A Full baseline measurements for TWR and AOA

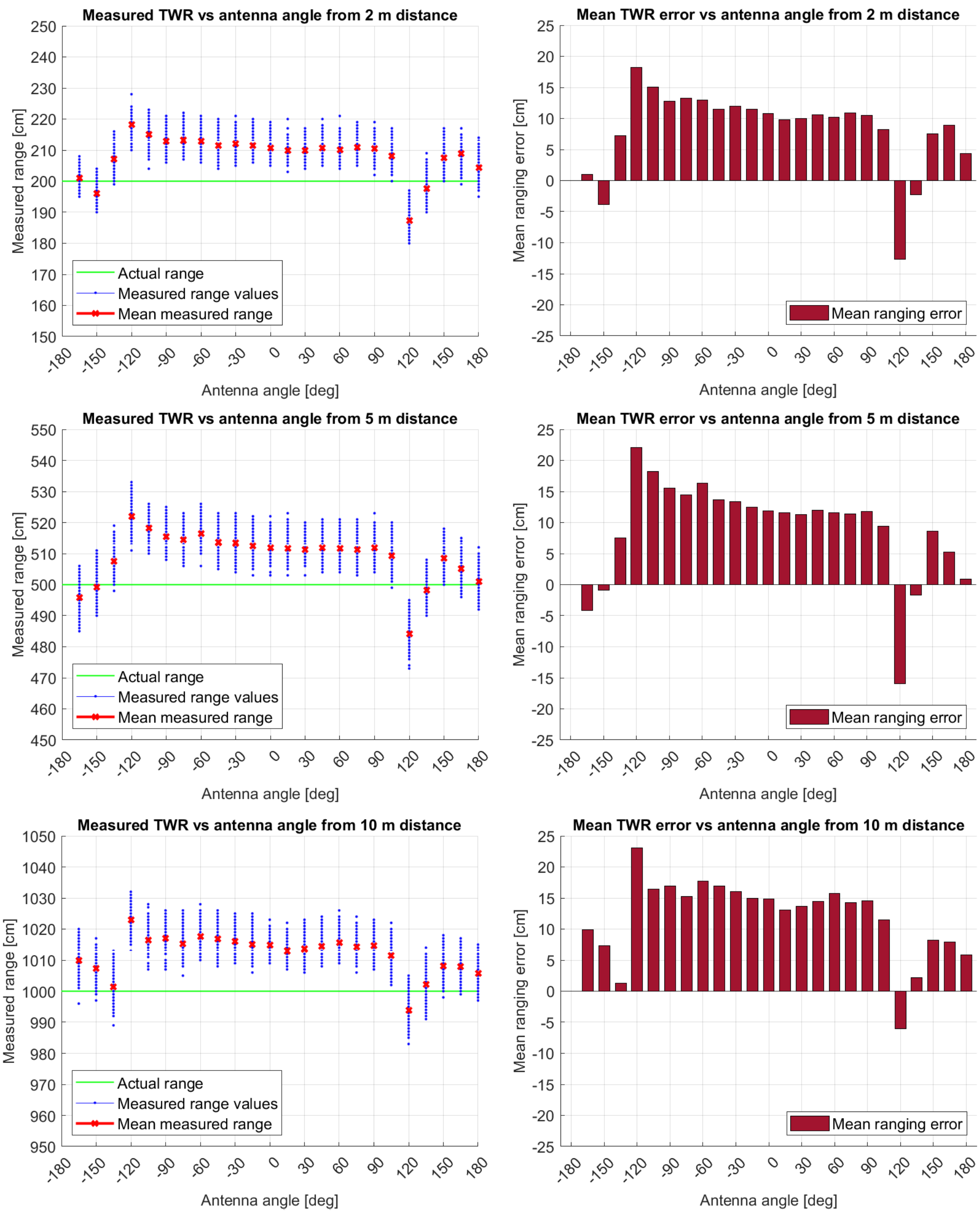

Figure A.1: TWR baseline. On the left column are are the the measurement results at each position (see graph title) and on the right the average deviation from the expeced values at each increment is plotted. First row is measured from 2 m, second from 5 m and third from 10 m distance.

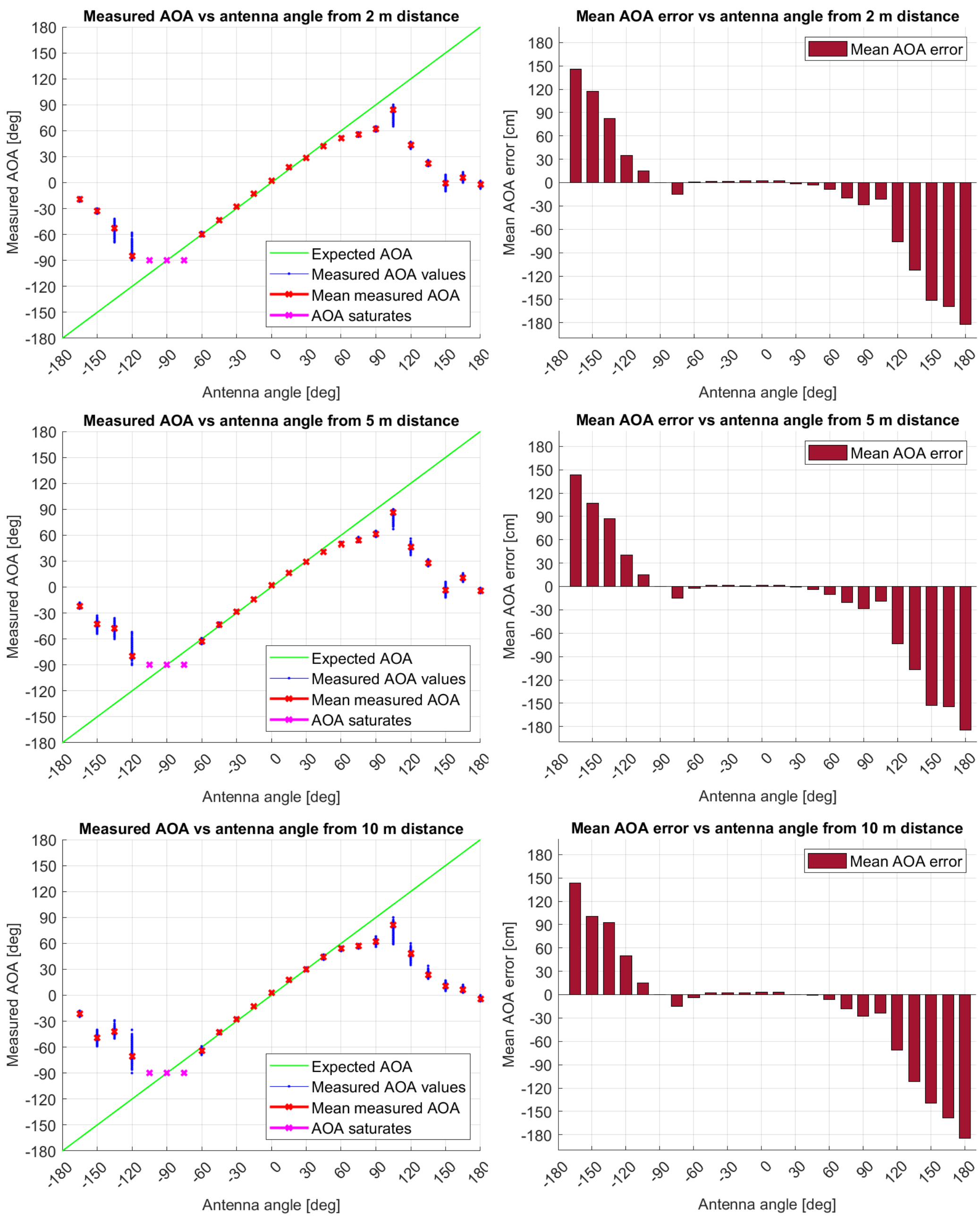

Figure A.2: AOA baseline. On the left column are are the the measurement results at each position (see graph title) and on the right the average deviation from the expeced values at each increment is plotted. First row is measured from 2 m, second from 5 m and third from 10 m distance.

B AOA conductors in front of or behind the antenna, full results

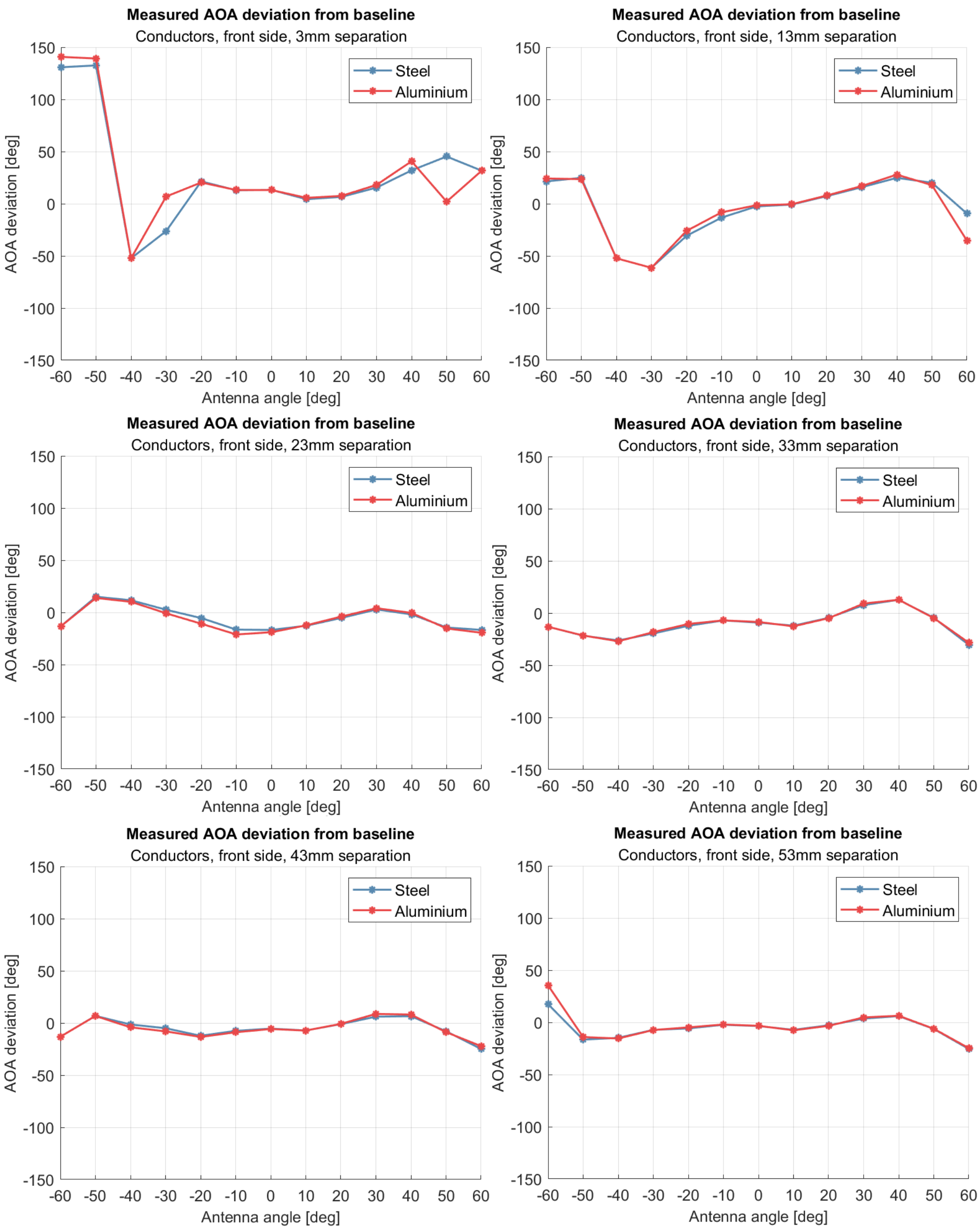

Figure B.1: AOA measurement results with steel (blue) and aluminium (red) in front of the DUT at different distances.

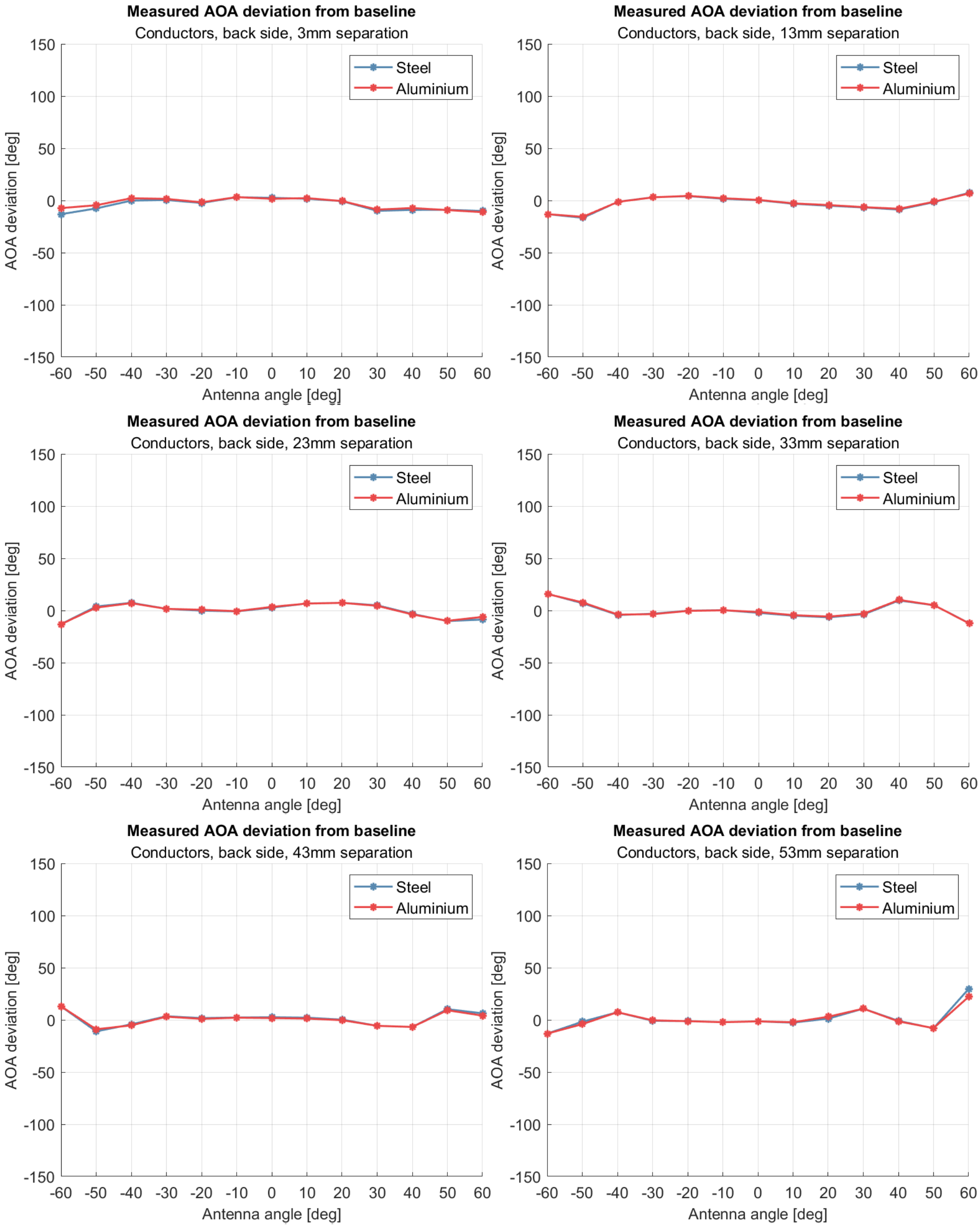

Figure B.2: AOA measurement results with steel (blue) and aluminium (red) behind the DUT at different distances.

C TWR, conductors in front of or behind the antenna, full results

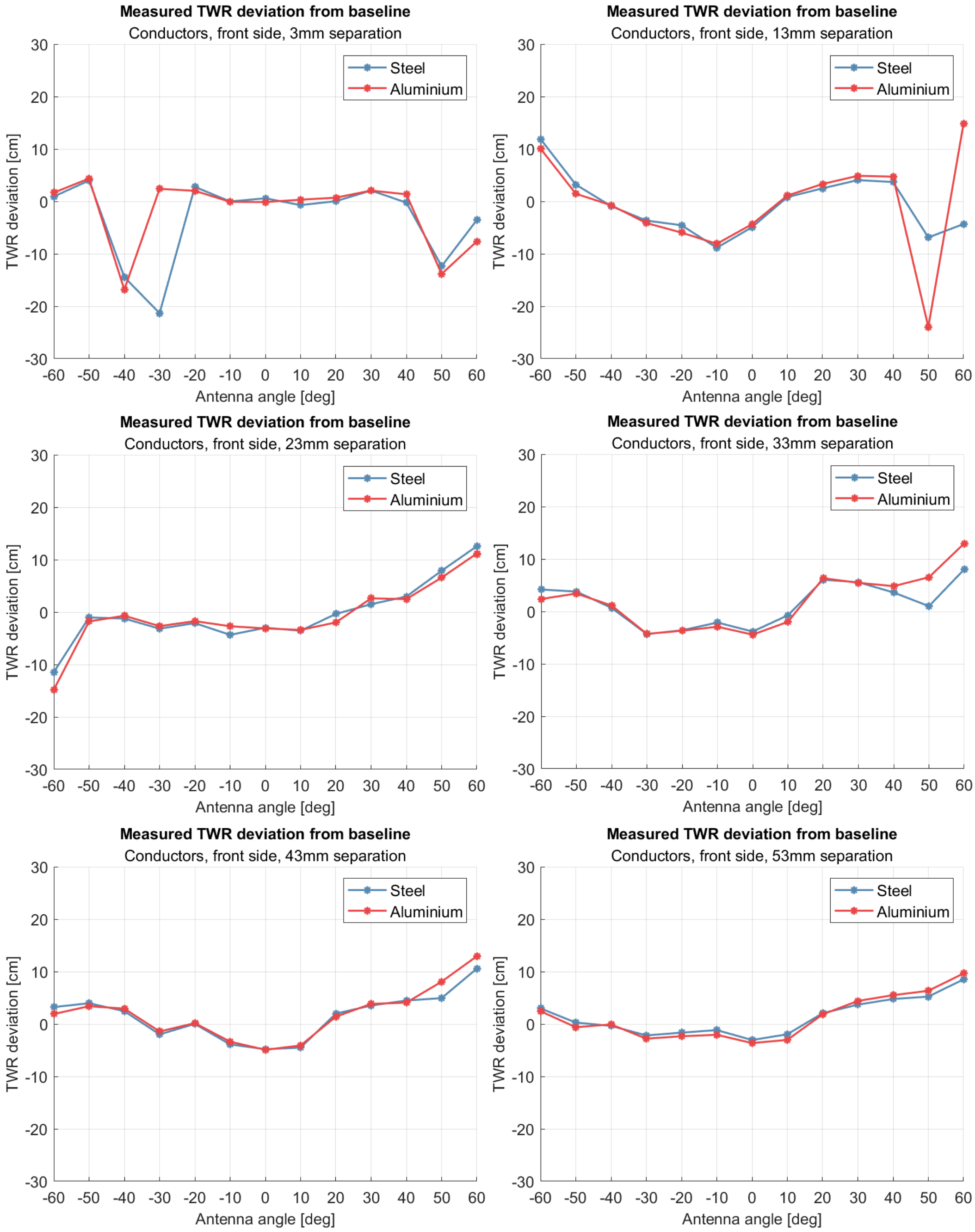

Figure C.1: TWR measurement results with steel (blue) and aluminium (red) in front of the DUT at different distances.

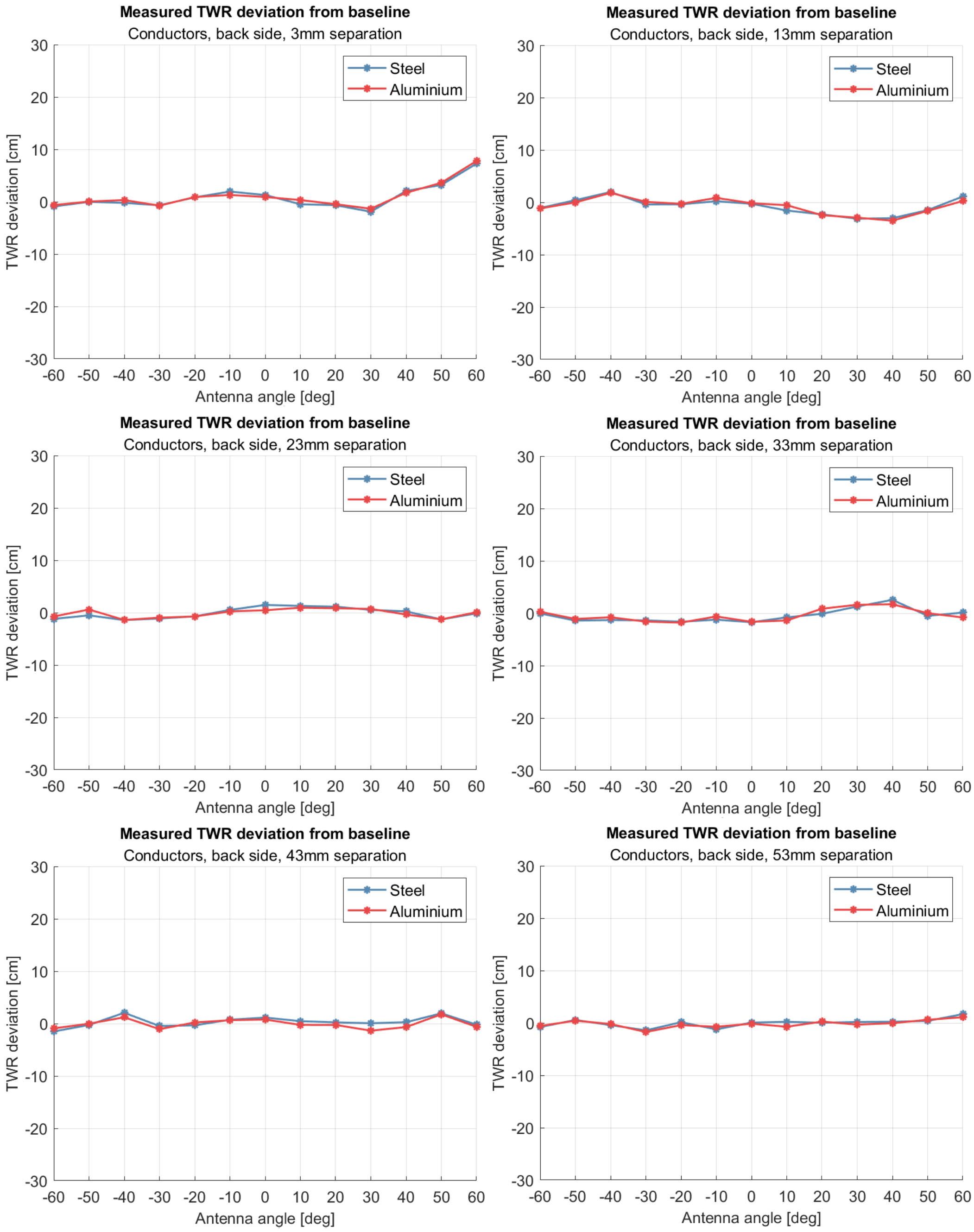

Figure C.2: TWR measurement results with steel (blue) and aluminium (red) behind the DUT at different distances.

D AOA, insulators in front of or behind the antenna, full results

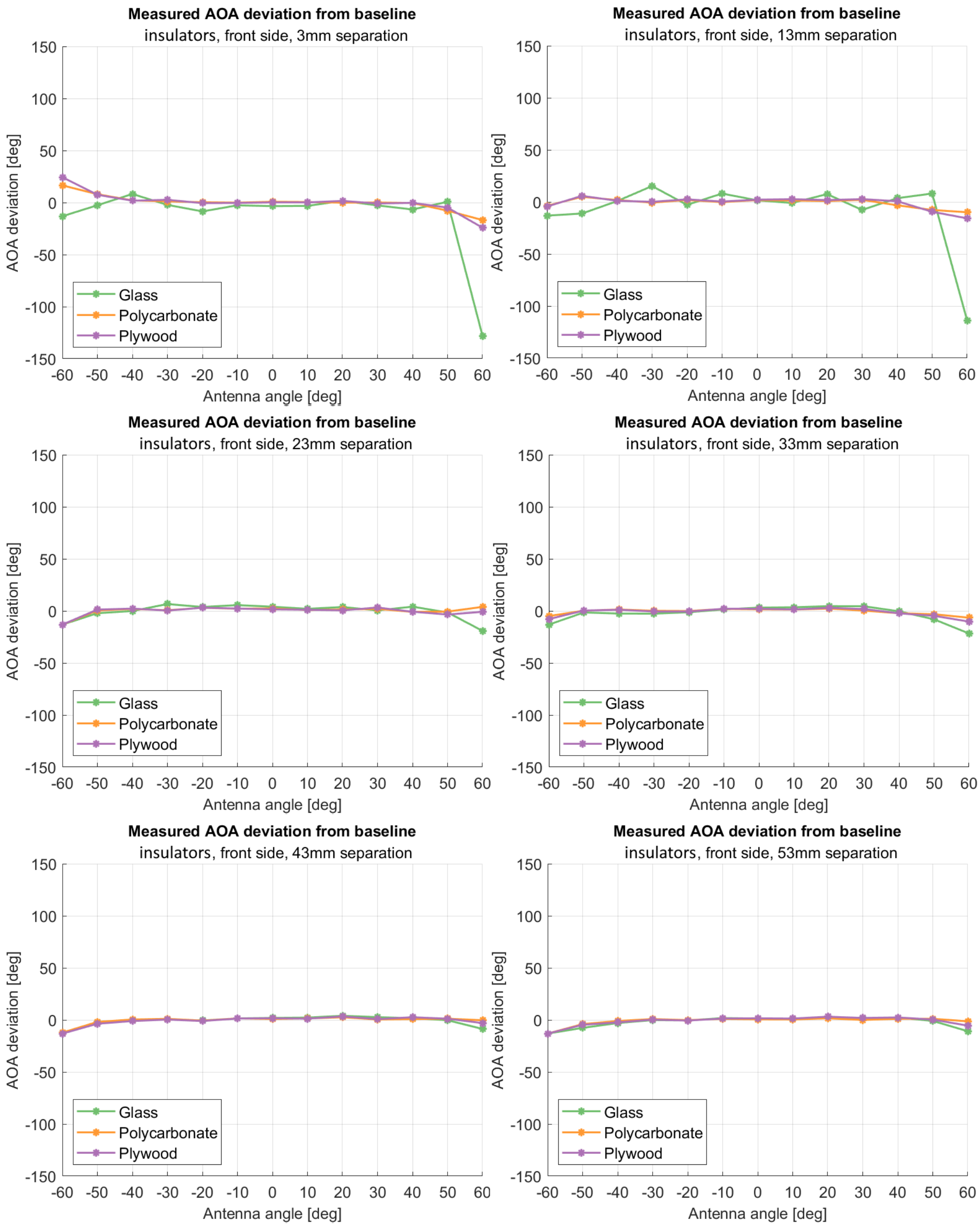

Figure D.1: AOA measurement results with glass (green), polycarbonate (orange) and plywood (purple) in front of the DUT at different distances.

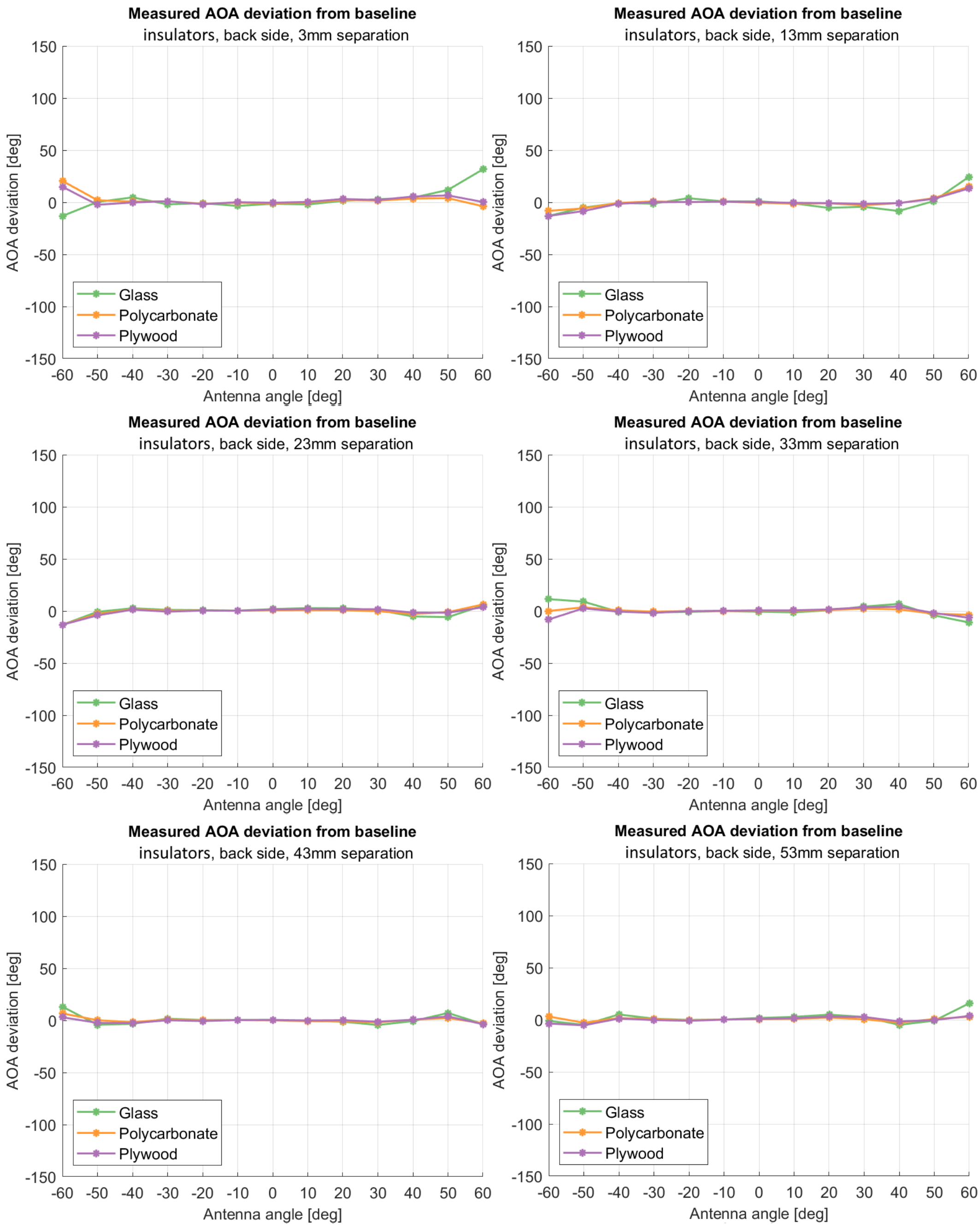

Figure D.2: AOA measurement results with glass (green), polycarbonate (orange) and plywood (purple) behind the DUT at different distances.

E TWR, insulators in front of or behind the antenna, full results

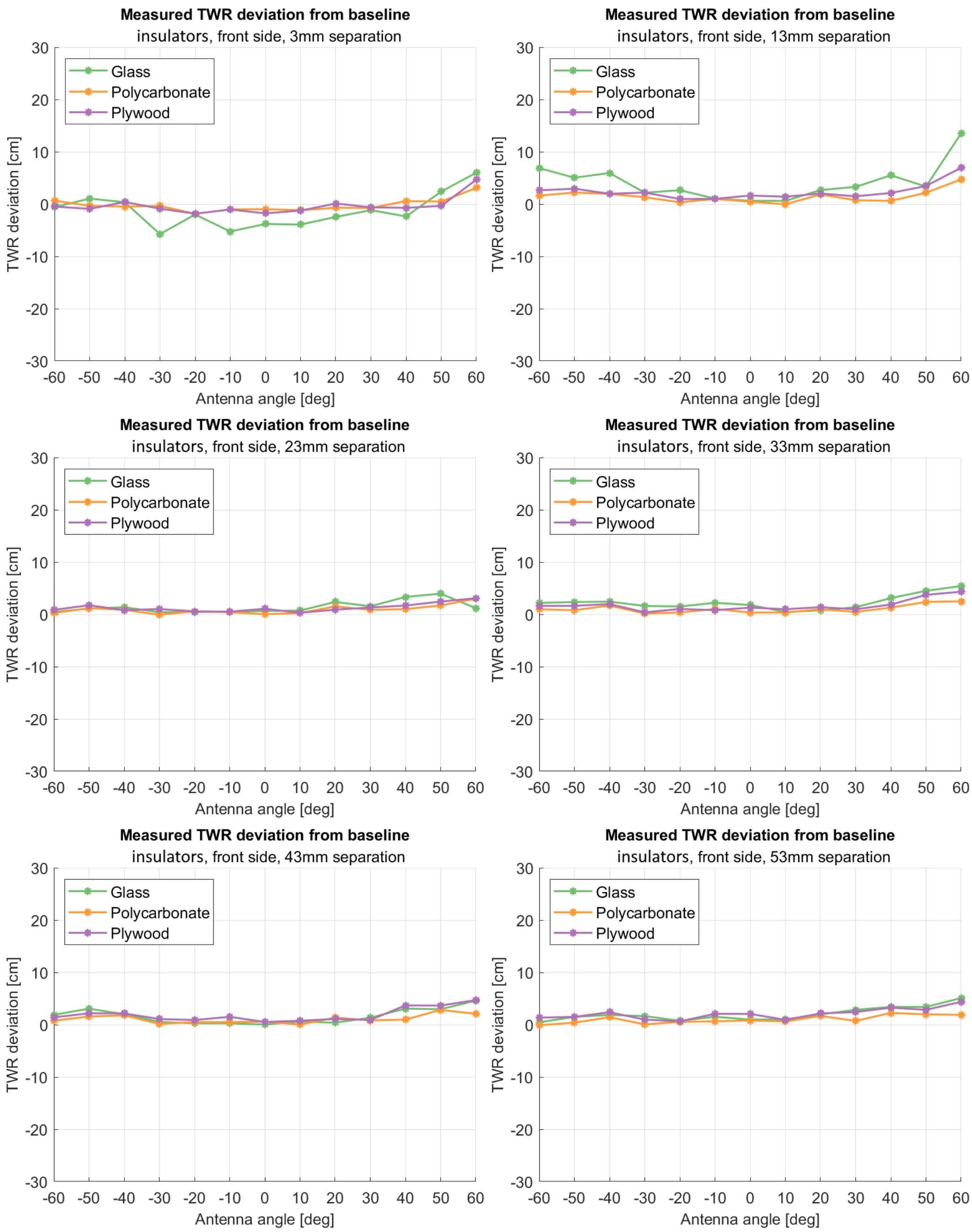

Figure E.1: TWR measurement results with glass (green), polycarbonate (orange) and plywood (purple) in front of the DUT at different distances.

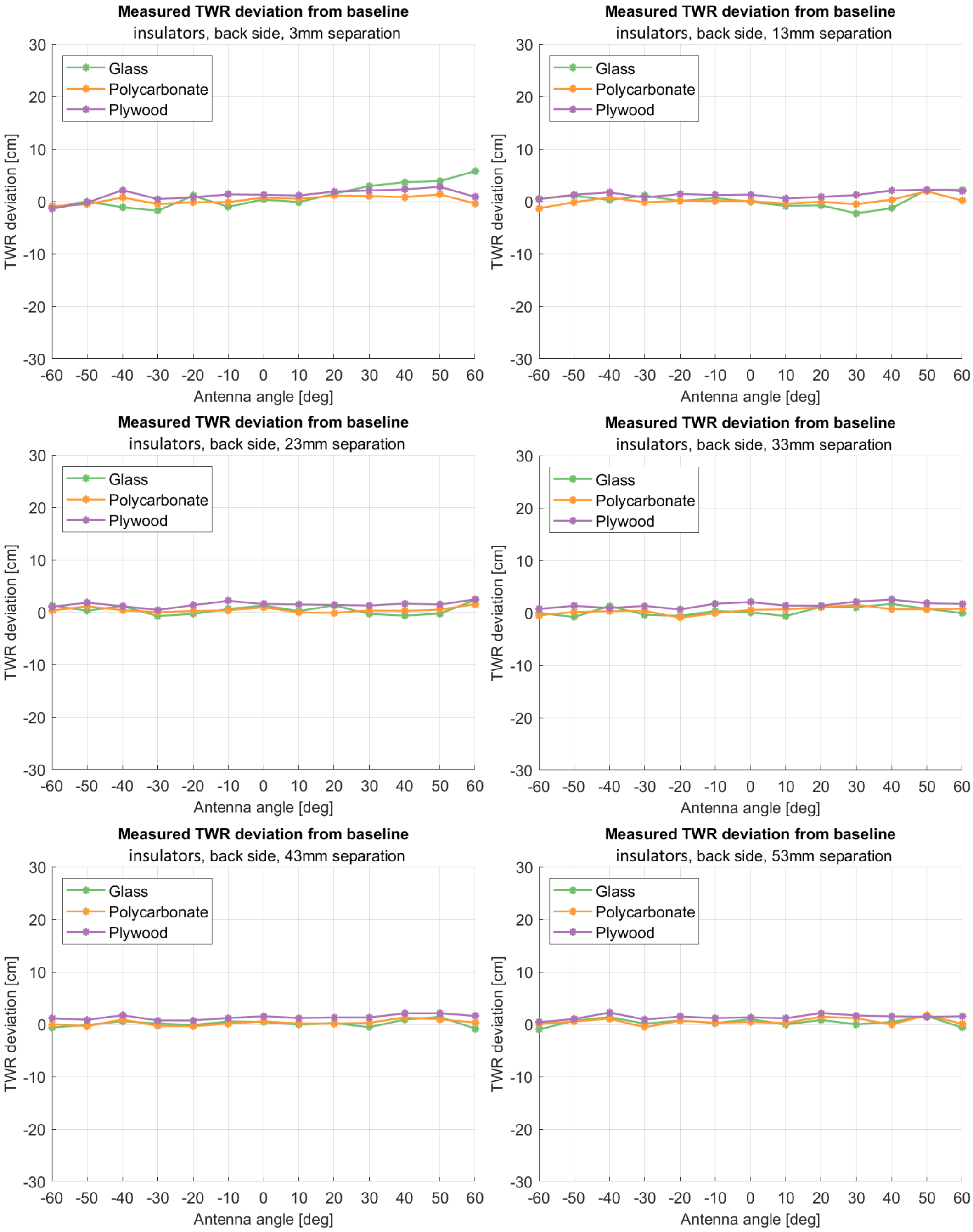

Figure E.2: AOA measurement results with glass (green), polycarbonate (orange) and plywood (purple) behind the DUT at different distances.

F APPENDIX: Microstrip patch antenna dimensions calculation example for 3D AOA on HRP PHY channel 9

In this example the minimum dimensions for an array of three antennas for 3D AOA estimation are calculated for HRP PHY channel 9, which is the mandatory channel on the high band. The center frequency of channel 9 is 7987.2 MHz and its bandwidth is 499.2 MHz. Let the substrate be FR4 which has a dielectric constant of 4.70, let the dielectric height be 1.6 mm (Malik et al., 2022). The configuration is going to be three rectangular patch antennas in a 90 degree angle for measuring the AOA on both x- and y-axis.

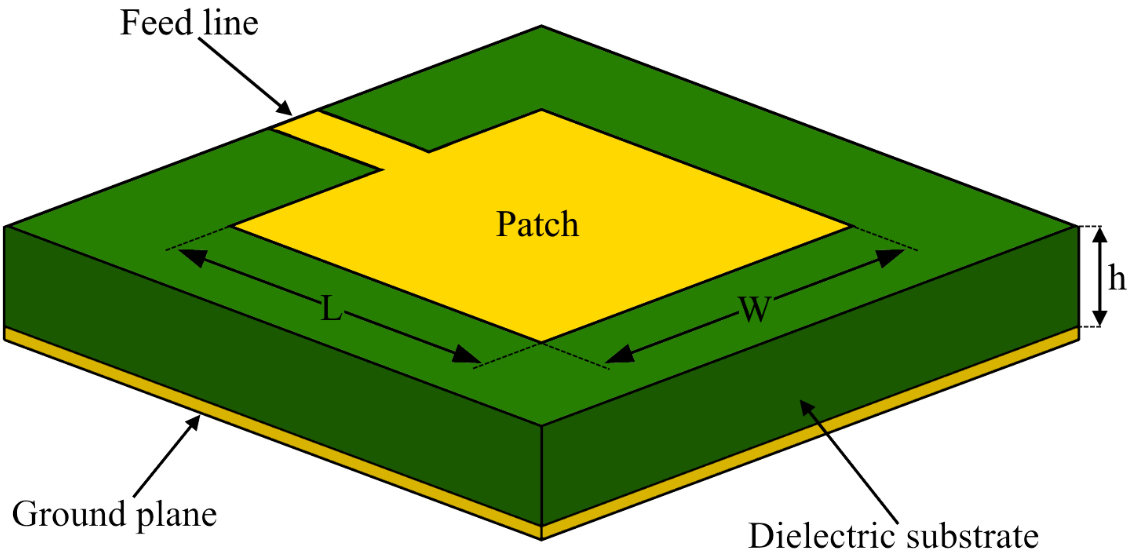

Figure F.1: Rectangular patch antenna dimensions.

First calculate the patch width for channel 9 with equation F.1:

$c = 3.0 \times 10^8 \frac{m}{s}$, $f_0 = 7987.2$ MHz , $\varepsilon_\text{r} = 4.70$, $h = 1.6$ mm

$$W = \frac{c}{2 \times f_0 \times \sqrt{\frac{\varepsilon_\text{r}+1}{2}}} = 11.028\,\text{mm} \tag{F.1}$$

Calculate effective dielectric constant, ε_eff with F.2:

$\varepsilon_\text{r} = 4.80$, $h = 1.6$ mm , $W = 11.028$ mm

$$\varepsilon_\text{eff} = \frac{\varepsilon_\text{r}+1}{2} + \frac{\varepsilon_\text{r}-1}{2} \times \left[1 + \frac{12 \times h}{W}\right]^{-\frac{1}{2}} = 4.7909 \tag{F.2}$$

and ΔL with F.3:

$\varepsilon_\text{eff} = 4.7909$, $h = 1.6$ mm , $W = 11.028$ mm

$$\Delta L = 0.412 \times h \times \frac{(\varepsilon_\text{eff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_\text{eff} - 0.258)(\frac{W}{h} + 0.8)} = 7.4029 \times 10^{-4} \tag{F.3}$$

And finally calculate the length of the patch with F.4;

$c = 3.0 \times 10^8 \frac{m}{s}$, $f_0 = 7987.2$ MHz , $\varepsilon_\text{eff} = 4.7909$, $\Delta L = 7.4029 \times 10^{-4}$

$$L = \frac{c}{2 \times f_0 \times \sqrt{\varepsilon_\text{eff}}} - 2 \times \Delta L = 7.0994\,\text{mm} \tag{F.4}$$

A single rectangular MPA for operation on HRP PHY channel 9 would have a width of 11.028 mm and a length of 7.0994 mm. AOA requires 2 antennas with D distance apart. The distance between individual antennas depends on the wavelength of the incoming signal and should be less than half of the wavelength, so for channel 9 (7987.2 MHz) the distance between antennas should be:

$$D = \frac{\left(\frac{c}{f_0}\right)}{2} = 18.78\,\text{mm} \tag{F.5}$$

The distance between antennas is measured from the antenna center, for 3D AOA three antennas at a 90 degree angle are required, see figure F.2. The dimensions of a single antenna are 11.028 mm × 7.0994 mm and the overall dimensions of the whole array is 25.8794 mm × 29.8081 mm, this does not include the extra space for the ground plane around the antennas.

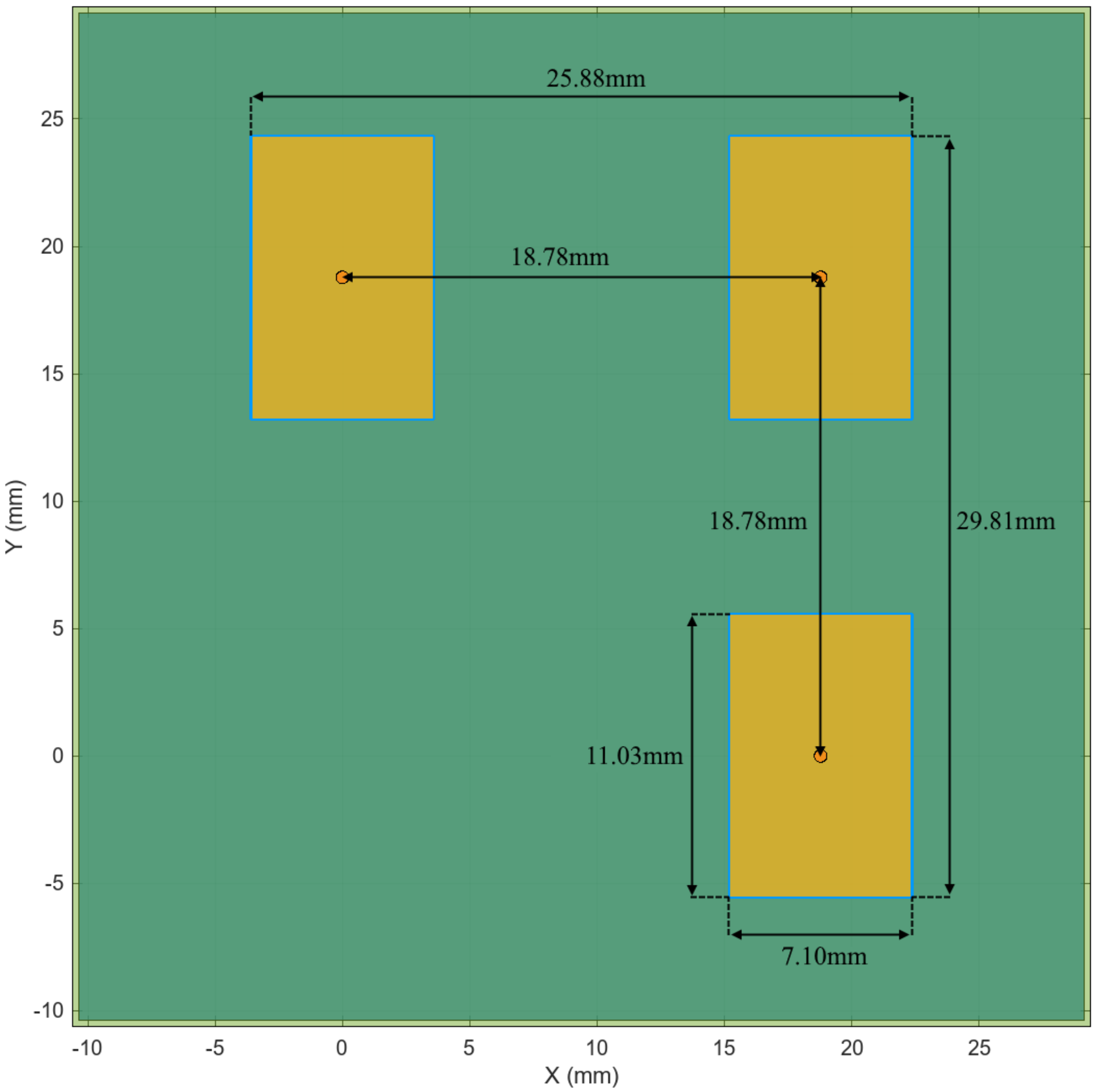

Figure F.2: 3D AOA array dimensions for HRP PHY channel 9.