Mechanical Antenna Beam Steering

SubTitle

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Bachelor of Engineering in Electronics, Spring 24

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STUDENT REPORT
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add colophon as the last thing!!

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Abstract:

In this semester project an algorithm is developed, that ...

Contents

Preface

This project was developed by Rikke Udengaard in the Spring semester of 2024 at Department of Electronic System at Aalborg University.

Aalborg University, April 20, 2024

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Chapter 1

Introduction

add abstract (last thing to do!!)

add introduction (second to last step!!)

Chapter 2

Technical Analysis

The purpose of beam steering is to increase the antenna gain in a specific direction to achieve reduction in interference and to save power. This is enabled by having the main lobe of a radiation pattern of a directional antenna pointing towards the target of transmission and reception. Beam steering is purposeful for narrow directional beams. Beam steering can be performed using manual, mechanical or electronic with the main differences being type of implementation and increasing speed of change of directivity from manual to electronic [11] [4]. This chapter explores the properties of antennas and beam steering methods, in order to understand antenna beam steering.

2.1 Fundamentals of Antennas

In order to develop a beam steering device for antennas it is necessary to understand antennas and their properties. Propagation, polarization, radiation characteristics are all properties of antennas that can vary based on the type of antenna.

2.1.1 Propagation In Free Space

Propagation of radio waves can be described with Maxwell's equations using the spherical coordinate system (r, θ, ϕ, t) for antennas. The Maxwell equations in differential form are as follows

$$\begin{aligned} \nabla \times \mathbf{E} &= -\frac{\partial}{\partial t}\mathbf{B} \\ \nabla \times \mathbf{H} &= \mathbf{J} + \frac{\partial}{\partial t}\mathbf{D} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \cdot \mathbf{D} &= \rho \end{aligned} \tag{2.1}$$

with **E** being the electric field with unit [$\mathrm{V\,m^{-1}}$], **B** being induction [T], **H** is magnetic field [$\mathrm{A\,m^{-1}}$], **D** being dielectric displacement [$\mathrm{A\,s\,m^{-2}}$], **J** being the current density [$\mathrm{A\,m^{-2}}$] and ρ being electric charge density [$\mathrm{C\,m^{-3}}$].

The electric field and the magnetic field are always connected; the electric field is created by the magnetic field and vice versa. The electric field and the magnetic field in spherical coordinates are illustrated on figure 2.1 below.

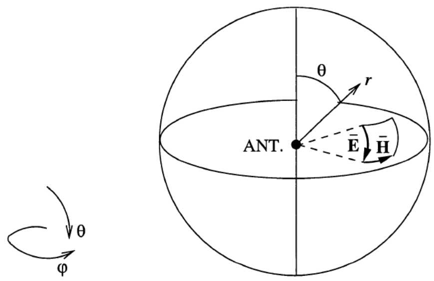

Figure 2.1: Electromagnetic field around a small antenna in far field range visualised in the spherical coordinate system [3, p. 58].

As visualised on figure 2.1 the electric field only depends on the θ-component and the magnetic field only on the ϕ-component when in the far field. The vector **r** is direction of the observation point. The length of **r** is the distance to the observation point ie. distance between transmitting and receiving antenna [3, p. 59].

The Poynting vector describes the power density and direction of the Electromagnetic flux and is the cross product of the electric and magnetic field

$$\mathbf{S} = \mathbf{E} \times \mathbf{H} \qquad [\mathrm{W\,m^{-2}}] \qquad (2.2)$$

which points in the same direction as the wave propagation [10, p. 3].

Multipath propagation

Because electromagnetic waves can reflect on surrounding surfaces, be changed by condition of the transmission medium or be Doppler shifted due to movement of objects, receiver or transmitter, the signal that reaches the receiving antenna can have travelled other paths than the direct line-of-sight path from the transmitter. The received signal is a summation of all input signals regardless of phase angles, phase shifts or direction and therefore the received signal might be distorted [8, pp. 1-2].

Aliasing

write about this

To prevent aliasing there must be a certain distance between the test device and the transmitting device, or in case of reflection measurement, half this length. The alias-free range is calculated as

$$Range = \frac{1}{\Delta f} V_f c \qquad [\mathrm{m}] \qquad (2.3)$$

where Δf is frequency step size, V_f is the velocity factor in the transmission line which is 1 for free space and c is the speed of light ($300 \times 10^6\,\mathrm{m\,s^{-1}}$). The frequency step size is equal to the measured frequency span divided by the number of discrete points in the span and is therefore dependent on the settings made on the network analyzer [12, p. 27].

2.1.2 Polarization

Different antenna designs have different radiation patterns and polarization. Table 2.1 lists a number of different antenna designs and their polarization

Type	**Polarization**
Isotropic antenna	
Dipole antenna	Linear
Patch antenna	Linear, circular
Horn antenna	Linear, cicular
Helical antenna	Circular

Table 2.1: Table showing polarization of some typical antenna designs [10, p. 11].

Polarization describes the classification of the plane propagated wave, which is a electromagnetic wave that propagates with constant velocity in a specific direction. The direction of the propagation of the electromagnetic wave is always perpendicular to the direction of the electric field **E** and both are perpendicular to the direction of the magnetic field **H**. If the direction of the electric field is constant with time and position, the polarization of the propagated wave is classified as linear. If the direction of the electric field changes by rotating uniformly around the axis of the propagated wave, the wave has circular polarization. The polarization of the receiving and transmitting antennas affects how the signal is detected. The signal is best received when the polarization of the receiving antenna is the same as the polarization for the transmitting antenna. Mismatch in polarization will result is less received signal power or more signal noise [7, p. 82-84].

2.1.3 Radiation Characteristics

The electromagnetic waves are radiated to the near field and then far field. The far field is mathematically described as the distance $r > R_2$, with R_2 defined as

$$R_2 = \frac{2D^2}{\lambda} \qquad [\text{m}] \quad (2.4)$$

with D being the largest dimension of the antenna or antenna array and λ being the wavelength of the carrier frequency [10, p. 4].

The radiation characteristics of an antenna can be described by the directivity, which is defined as the ratio of the maximum power density $S(\theta,\phi)_{max}$ radiated to the average power density $S(\theta,\phi)_{avg}$ radiated by an antenna. The directivity is unitless [7, p. 63]. An isotropic antenna is a theoretical antenna which radiates homogeneously in all directions, meaning that the magnitude of the power density vector $\mathbf{S}$ at a distance vector $\mathbf{r}$ is constant

$$D(\theta,\phi) = \left| \frac{S(r,\theta,\phi)}{S_{max}} \right| = 1 \quad (2.5)$$

It is this theoretical isotropic radiator that the gain of antennas are in respect to. The gain of a directive antenna in a certain direction is called the antenna gain G [10, p. 12]. The directivity doesn't depend on the distance r in the far field meaning that at the receiver antenna, the relation $r \gg R_2$ is assumed.

The total radiated power P_r is found by the surface integral of the power density. Assuming a spherical surface, the total radiated power is described as

$$P_r = \int_0^{2\pi} \int_0^{\pi} S(\theta,\phi)\, r^2 \sin\theta \, d\theta \, d\phi \qquad [\text{W}] \quad (2.6)$$

And further, averaging the radiated power over every direction in the sphere gives the relation

$$P_{avg} = \frac{P_r}{4\pi r^2} \qquad [\text{W m}^{-2}] \quad (2.7)$$

Replacing the average power density $S(\theta,\phi)_{avg}$ by the average power in every direction P_{avg}, the directivity of an antenna $D(\theta,\phi)$ can be defined as

$$D(\theta,\phi) = 4\pi r^2 \frac{S(\theta,\phi)_{max}}{P_r} \quad (2.8)$$

with $S(\theta,\phi)_{max}$ being the maximum power density and P_r being the total radiated power of the antenna.

The power of the source $P_{s,t}$ to a transmitting antenna might not equal the radiated power $P_{r,t}$ due to power loss $p_{l,t}$. Power loss can happen because of reflection loss in the input medium (typically cable), conductor loss and inductor loss. The efficiency of the transmitting antenna η is described as the ratio of the radiated power to the sourced power

$$\eta = \frac{P_{r,t}}{P_{s,t}} = \frac{P_{r,t}}{P_{r,t} + P_{l,t}} \tag{2.9}$$

The gain $G(\theta, \phi)$ of the antenna is the effective directivity, meaning how well the receiving or transmitting antenna is able to convert, respectively, electromagnetic waves or power into the other. The gain of a transmitting antenna can be calculated as

$$G_t(\theta, \phi) = \eta D_t(\theta, \phi) = 4\pi r^2 \frac{S_t(\theta, \phi)_{max}}{P_{s,t}} \tag{2.10}$$

or expressed in decibel with respect to the isotropic radiator [10, p. 10] [13, pp. 1.8-1.10].

$$g_{dBi} = 10 \log_{10}(G) \qquad \text{[dB]} \tag{2.11}$$

Friis Transmission Equation

The Friis transmission equation explains how the received power at a receiver antenna is related to the power of the transmitting antenna. The receiver antenna receives energy from the transmitting antenna and the effectiveness of this is described as the effective area $A_r(\theta, \phi)$ assuming that the antenna is placed in the origin of the spherical coordinate system. If the antenna has the property of reciprocity, the effective area and the gain of the receiver antenna is related by

$$A_r(\theta, \phi) = \frac{\lambda^2}{4\pi} G_r(\theta, \phi) \qquad [\mathrm{m}^2] \tag{2.12}$$

If the gain of the transmitting antenna G_t is in the direction of the receiver antenna G_r then the angular dependencies of the antenna properties can be surpressed. The power of the receiving antenna is equal to the power density $S_t(\theta, \phi)$ multiplied by the effective area of the receiver antenna A_r, expressed as

$$P_r = S_t A_r \qquad \text{[W]} \tag{2.13}$$

As previously mentioned the directivity of an antenna does not depend on the distance r from the antenna, and likewise so with the power density S_t, so the value of S_t is equal regardless of the distance from the antenna in the far field with respects to the angular dependencies. Substituting S_t and A_r in equation 2.13 for S_t isolated in equation 2.10 and A_r from equation 2.12 yields

$$\begin{aligned} P_r &= \frac{G_t P_t}{4\pi r^2} \frac{\lambda^2 G_r}{4\pi} \\ &= G_t G_r P_t \left(\frac{\lambda}{4\pi r} \right)^2 \end{aligned} \qquad \text{[W]} \tag{2.14}$$

Also called Friis transmission equation [13, pp. 1.10-1.11]. G_t is the gain of the transmitting antenna in the direction of the receiver and G_r is the gain of the receiving antenna in the direction of the transmitter. The radiation characteristics of an antenna in the far field is called the antenna radiation pattern and will look different depending on the design of the antenna. The radiatation pattern is dependent on the anglular properties θ and ϕ and is usually visualised in a plane parallel to the electric field and called an **E** plane pattern or elevation plane pattern, or parallel to the magnetic field and called a **H** plane pattern or Azimuth plane pattern [7, p. 79-80][10, p. 13-14].

Antenna Design

The design of the antenna affect the radiation characteristics, the bandwidth and the range of frequencies that the antenna is able to transmit or receive [7, p. 76]. The antenna types described in table 2.1 are some of the typical design types along with the isotropic antenna which is a theoretical antenna [10, p. 11].

A dipole antenna is two wires or rods pointing at the opposite direction of each other, for example towards positive and negative z in the spherical coordinate system. In the Azimuth plane the radiation pattern is a circle centered at the centre of the dipole antenna, whereas in the elevation plane, the radiation pattern is two ears extending from the centre to either side (see figure 2.2 and 2.3) [10, pp. 12-14].

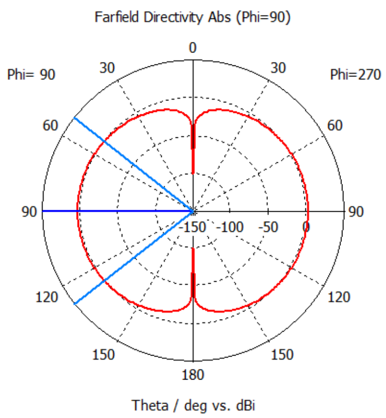

Figure 2.2: Dipole antenna radiation pattern in the Azimuth plane.

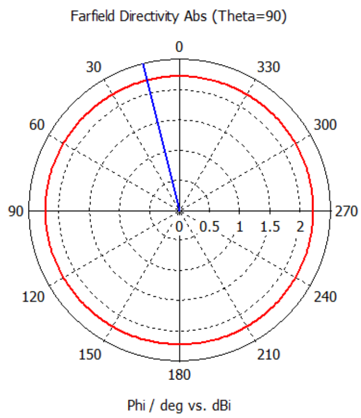

Figure 2.3: Dipole antenna radiation pattern in the elevation plane. Figures generated with *CST Studio* dipole antenna example ($f = 2.4\,\mathrm{GHz}$).

The dipole antenna is good at ?? and bad at ?? and it can also be configured differently like a yagi antenna and ??

dipole

A patch antenna ????

patch

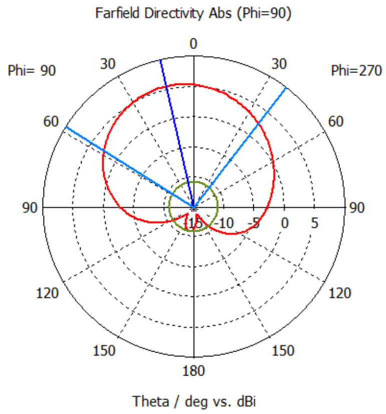

Figure 2.4: Patch antenna radiation pattern in the Azimuth plane.

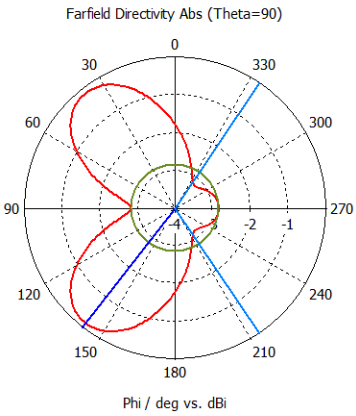

Figure 2.5: Patch antenna radiation pattern in the elevation plane. Figures generated with *CST Studio* ($f = 2.4\,\mathrm{GHz}$).

Horn antennas come in many shapes and sizes which affect the radiation pattern and gain but common amongst the different designs is high beam directivity [13, p. 14.1]. A rectangular horn antenna has a fan-shaped radiation pattern and the beamwidths of the fan can be changed by the varying the aperture dimensions ?????

horn

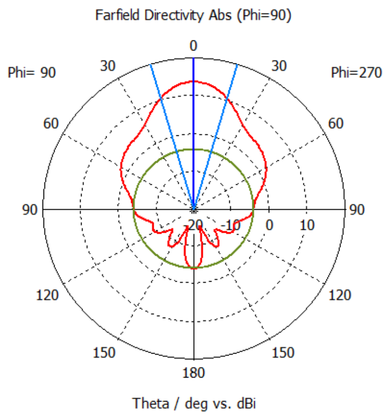

Figure 2.6: Horn antenna radiation pattern in the Azimuth plane.

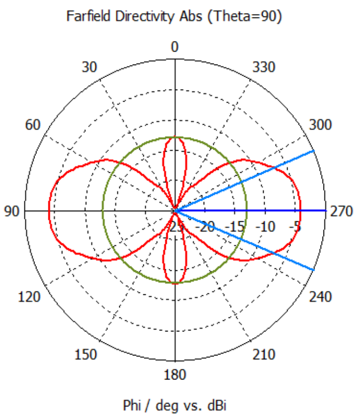

Figure 2.7: Horn antenna radiation pattern in the elevation plane. Figures generated with *CST Studio* horn antenna example ($f = 2.4\,\mathrm{GHz}$).

A helical antenna ???

helical

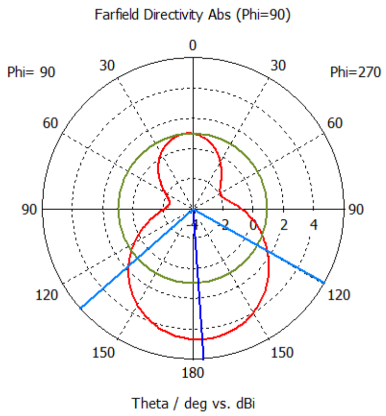

Figure 2.8: Helical antenna radiation pattern in the Azimuth plane.

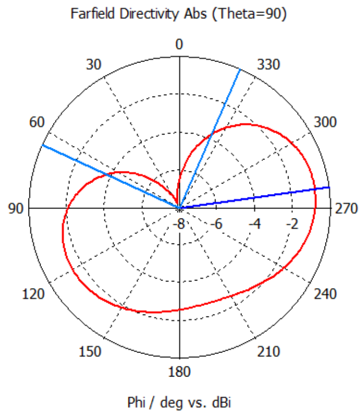

Figure 2.9: Helical antenna radiation pattern in the elevation plane. Figures generated with *CST Studio* ($f = 2.4\,\mathrm{GHz}$).

Antennas can also be put together in arrays. This changes the characteristics of the radiation pattern and ??

arrays

2.2 Beam Steering Methods

Beam steering can be done manually, mechanically or electrically.

2.2.1 Manual and Mechanical Steering

explain motor control and types of motors with type of control loops

2.2.2 Electrical Steering

Chapter 3

Requirements and Delimitations

The purpose of this project is to develop a setup where a receiving antenna is able to detect a transmitting antenna at a abitrary point in space and testing this setup. Detection of radio waves can for example be used for intruder detection or can be further developed to include data transmission and thereby achieving higher troughput if the transmitting antenna is able to locate and focus on the receiving device.

Concluding on these two scenarios, it is required that the receiving antenna must be able to be controlled ie. steered in any direction and the electromagnetic radiation in the area must be read.

3.1 Delimitations

The setup developed in this project will only be designed to be able to work in a two-dimensional plane. Moreover, in order to be able to reproduce the test results, the environmental variables such as objects in the space, size of space, temperature and humidity must be controlled and measurable.

3.2 Functional Requirements

The following table 3.1 outlines the functional requirements:

ID	Requirement	Traceability
F.1	Mechanically controlled turning along Azimuth angle ϕ	Chapter 3 introduction, section 3.1
F.2	Data reading of electromagnetic radiation in the surrounding space	Chapter 3 introduction, section 3.1
F.3	Controlled test environmental variables	Section 3.1

Table 3.1: Table of functional requirements.

3.3 Technical Requirements

outline in table technical requirements. Remember environmental requirements temp and hum

ID	Requirement	Traceability
T.1	Operating temperature of ??	?
T.2	Operating humidity of ??	?
T.3	Matching antenna polarization	?
T.4	Automatic, (speed?) control	?

Table 3.2: Table of technical requirements.

Chapter 4

Design of Antenna Beam Steering

short introduction

4.1 Antenna Design

explain design of horn antenna and why

In order to prevent aliasing the alias-free range must be calculated. As described in section 2.1.1 the range depends on the settings on the network analyzer. The frequency span together with the number of points also affect how fast each measurement of the entire span can be made.

describe what happens with each setting + what sweep frequency(?) does

The frequency span is chosen from 5 GHz to 7 GHz which is most of the range of which the horn antenna is designed to work in. The number of points is chosen to be 1001 because lowering this value by a couple factors will affect the measurement speed negatively. Therefore the alias-free range is

$$Range = \frac{1001 - 1}{5 \times 10^9\,\mathrm{Hz} - 7 \times 10^9\,\mathrm{Hz}} 300 \times 10^6\,\mathrm{m\,s^{-1}} = 150 \qquad [\mathrm{m}] \tag{4.1}$$

4.2 Choice of Turntable

explain choice of turntable and how it meets reqs

4.3 Choice of Vector Network Analyzer

explain choice of vna and how it meets reqs

4.4 Design of Software Control Program

explain design principles of software

The control of the turntable and VNA is programmed in Python. The control of the turntable is implemented as adviced by the manual (see [6]), with the supplied software *RC-HRT I*. However, in order to control the turntable concurrently with the VNA, the *RC-HRT I* software is controlled via Python with the module *pywin32*, which provides access to the Microsoft Windows APIs [1] and therefore makes the *RC-HRT I* software controllable in Python. *Rohde & Schwarz* have published a Python module for control of the VNA which is used. Finally, thread parallelism is achieved with the module *threading*.

The communication with the turntable and the VNA are handled internally in the Python modules that instead provide a functional, high-level interface. However, the communication protocols and interfaces that the turntable and VNA require, do affect the design of the control software.

4.4.1 Communication Interfaces

explain communication to and from vna and tt in depth

The communication interfaces of the program is limited by the choice of the turntable and VNA. The *HEAD Acoustics, HRT I* turntable that has been chosen can be controlled by serial communication using the RS485 standard [5]. The *R&S ZVB8* VNA has a LAN type interface for control and data transfer and ?? [9].

4.4.2 Concurrency

As previously written, the turntable is controlled via serial communication while the data from the VNA is read via a network cable and TCP. Python serial communication and the communication with the VNA are both I/O bound tasks. Therefore, in order to achieve real-time communication and data processing the wait time of the I/O bound operations is exploited by use of the Python module *Threading*. *Threading* uses a single processor and pre-emptive multitasking to acheive concurrency [2].

explain how program runs

Chapter 5

Tests

This chapter includes test descriptions and results to validate the design against the requirements. First, the two directional antennas are tested to find their gain and ensure, that the transmitter and receiver have their maximum gain at the same frequency. Finally, the full test of the beam steering and transmitter locator is tested with the transmitter fixed at a known location in the test area.

5.1 Test of Gain in Frequency Spectrum

The aim of this test is to test both directive antennas in a frequency spectrum to ensure they operate at the same frequency.

elaborate and do test

5.2 Test of Radiation Pattern

The aim of this test is to know the directiveness of the two directional antennas.

elaborate and do test

5.3 Accept Test

The aim of this test is to test the full function of the developed product. The test must show that the receiver antenna on the turntable is able to scan the test area and measure the received power at fixed angles, before selection the location with the maximum received power and focusing its beam on that location.

elaborate introduction

Equipment

To perform the test, the following equipment is needed:

- HEAD Acoustics Remote-operated Turntable, model HRT I 6498, with 24 V DC 60 W power supply
- D-sub 9-pin to USB-A cable
- PC with one USB-A port and one LAN port
- Rohde & Schwarz ZVB 8 Vector Network Analyzer
- Network cable (8-pin RJ-45 connector)
- Two 50 Ω directional antennas with XX frenquecy
- power supplies to the antennas ????

find exact values and names

Moreover, the test must be performed in a controlled environment, where the temperature is not below 0 °C or above 50 °C with a relative humidity in the range 20 % - 80 % [5].

add VNA environmental conditions

Test Execution

The following steps outline how to perform the test:

1. Do this. Refer to figure 5.1 to visualise the setup.

elaborate on the how

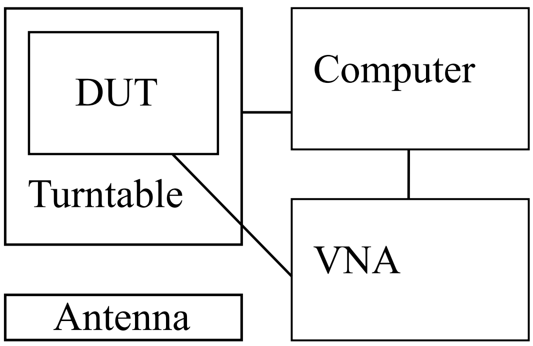

Figure 5.1: Setup for test of functionality of beam steering device.

improve this figure because it is ugly. Needs more names

5.4 Test Results

add table for test results and describe

5.4.1 Test errors

While the turntable is turning the cable connected to the horn antenna will move with it. This will affect the phase of the signal. However, since the purpose of the test is to measure magnitude, this error is will not effect the test result.

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