Deep Learning Neural Network for Tuning of the Optical Beamforming Networks

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LITERATURE SURVEY

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Abstract

In an aircraft-satellite communications, the aircrafts transmit highly focused beams that are steered exactly towards the satellites. Conventional solution for this problem is to steer the dish antennas mechanically in order to direct the beam. Optical Beamforming Networks (OBFNs) instead, rely on many small and flat antennas that are coordinated in order to generate highly focused beams. In this project, a new type of OBFN proposed by Meijerink et al. [1] will be considered. The correct tuning of these OBFNs such that the beam is steered correctly is a difficult nonlinear problem that, so far, has only been addressed with off-the-shelf solvers in very small setups.

The problem of tuning a large-scale OBFN is very similar to training a neural network. For the later problem, many recent advances have been made under the umbrella term deep learning. The objective of this graduation project is to explore if and how advances in deep learning can be exploited to train the OBFNs. This can be achieved either by formulating the tuning problem as a learning problem, or by modifying existing algorithms in the area of deep learning. The tuning methodology developed in this project is based on feedback that can be measured in real systems (e.g., output power).

The literature survey is divided into two distinct parts. In the first part, we analyze the current setup and algorithm of OBFN proposed by Blokpoel [2] and Meijerink et al. [1] with special emphasis on the power optimality criterion. The analysis covers a whole concept of Antenna System, including Antenna Elements (AEs), OBFN based on binary tree topology, Optical Ring Resonators (ORRs), as well as the ORR's parameters and their influence to the group delay of the signal. The second part uses the theoretical information from the first part to support the implementation of deep learning neural network for solving a more general setup of OBFN without any limitation to small setups. This part handles the implementation of the concept of deep learning neural network to train the tuning of the OBFN.

It is expected that .... (advantages of using neural network concept rather than current concept)

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Preface

This is document is a part of my Master of Science graduation thesis. The idea of doing my thesis on this subject came after my scholarship committee, The Ministry of Communication and Information of the Republic of Indonesia required me to do research on the communication field. I remembered, Prof. dr. ir. Michel Verhaegen once presented some projects of his current research, and one of them is the project of control of airplane communication. I, later, contacted him asked about this project, and he then introduced me to my thesis supervisor, Dr. Sander Wahls whose expertise in communication.

The most important technical acknowledgment is made to Dr. Sander Wahls, for providing me with guidance and opportunities for learning telecommunication, a field which I am interested to yet not experienced in. I would also like to thank Laurens Bliek for his constant support and willingness to discuss the problems I have encountered in this project.

Moreover, I would like to thank all my friends with whom I traveled, shared incredible memories, laughter and joy. Finally, I would like to deeply thank my family who have supported me in all my endeavours and motivated me to aim higher.

An additional technical note is required: if any typo or incorrect information is detected please contact me via `herminarto.nugroho@gmail.com`

Chapter 1

Introduction

Optical group delays are of great importance nowadays in optically-controlled Phased Array Antenna (PAA) system. PAA system offers several advantages when compared to mechanically steered antennas, such as agile beam steering, relatively low maintenance cost, reduce drag force when applied in for instance vehicle and aircraft, and the possibility of supporting multiple antenna beams [4].

A PAA system consists of an array of multiple Antenna Element (AE), corresponding transmission and/or reception units, and a beamformer. AE signal consist of a time-delayed version of some desired signals, possible time-delayed version of of some undesired signals (from different direction), and noise (sky noise and antenna noise). The values of these delays are different for each AE, depends on the geometrical distribution of the AE locations, and for sure the direction of the incoming/outcoming wave-front signals. The beamformer consists of a delay-and-combine network that equalizes the delay values of the desired signal, such that the desired signal adds up in phase and reinforced, whereas the undesired signal do not add up and hence suppressed [1]. It is desirable that the time-delays are tunable, in order to be able to alter the reception angle of the PAA.

In this thesis, a seamlessly tunable optical beamformer concept proposed by Meijerink et al. [5] is used. It is based on coherent optical combining in an Optical Beamforming Network (OBFN) using cascades of Optical Ring Resonator (ORR) [6, 7] as tunable delay elements. With the structural enhancement (resonance) characteristic, the ORR filters are able to generate a tunable group delay, which could be larger than the unit delay of the filter (the roundtrip time of the light). Thermal tuning mechanism is used in the filter, which is characterized by the high accuracy in the tuning process [8].

A Non-linear Programming (NLP) optimization is one of the methods used to determine the parameters of the ORR thermal tuning mechanism. This method converts a desired delay value into a set of optimal parameters of the respective ORR. The first step of this method is to derive the optimality criteria. There are three optimality criteria, which are delay, phase and power criterion. From that three algorithms, an NLP solver is used to find the optimal solution. This method was proposed by Blokpoel [2]. However, that method uses normalized

bandwidths and target delays, and assumed the group delay response to be symmetric which shows its lack of generality. It is not desirable since it will limit the application of the one particular setting for the general case. Therefore, a more general method is proposed.

((((introduction about deep learning neural networks as an alternative solution))))

Taking the aforementioned premises into consideration, the goal of the thesis can now be presented.

1-1   Goals of the Thesis

The main goal of the thesis is to provide a general method and algorithm for tuning the OBFN, yielding better result without limitation on any binary tree OBFN topology. This method will solve the basic problem the current tuning method (Non-linear Programming Optimization) has, which is designed to tune the OBFN for a specific topology. This boils down to answer one question which is the fundamental problem of this thesis:

"Is there a method that allows us to tune the OBFN for a general (in terms of topology and algorithm) and thus outperform the current Non-linear programming optimization method?"

1-2   Research Approach

Based on the main goal of the thesis, the research approach can be divided into two parts containing several topics that must be addressed.

(((((topics to be addressed)))))

1-3   Nomenclature

Row or column vectors are represented using boldface lower-case symbols such as $\mathbf{x}$. Boldface and upper-case symbols, such as $\mathbf{A}$, are used for matrices. Regular font, x_1, denotes a scalar variable.

(((((edit every time needed)))))

Chapter 2

Phased Array Antenna and Optical Ring Resonator: An Overview

In the last century, radio systems have become an essential way to pass on signals by means of the transmission of electromagnetic waves with frequency below the visible light. In the recent years, increasing demand for fast information exchange motivated the development of many ideas of broadband radio applications. People wish to be able to connect to internet, participate in teleconference, or watch live TV no matter where they are, especially when traveling on a long intercontinental flight. This demand motivated the development of communication between satellite and aeroplanes.

In the application of the radio described above, the system is featured by the radio link with low signal power density. therefore, high-gain and direction-sensitive antennas are essentially required for the signal reception. The ordinary omni-directional antenna is not preferable because, although it is an directional-sensitive antenna, it has low gain [9].

A conventional solution for a direction-sensitive antenna is a dish antenna, which can be steered mechanically to the point its main beam to a desired directions [10]. Even though it is direction-sensitive and has high-gain, a dish antenna is slow because its speed is limited by the mechanical movement. The mechanical movement also have negative effect on the tuning precision. Another drawbacks are its large weight, large size, and aerodynamic drag effect when mounted on top of a plane. It also has difficulty for the maintenance. Instead of using a dish antenna, the more advantageous alternative is to use a Phased Array Antenna (PAA) [11, 12]. The explanation of PAA will be covered in the first section of this chapter.

2-1 Phased Array Antenna

A PAA consists of an array of Antenna Element (AE). The antenna pattern is determined by the geometry of the array as well as the signal amplitude and phase relation between the AEs. The main beam of the PAA can be steered without any mechanical movement

involved. It is possible by changing the amplitude and the phase relation of the AE signals. To control both the amplitudes and phases of the AE signals, the so-called beamformer is required. Conventionally a beamformer is realized in the electrical domain. However, it can also be realized in the optical domain: an photonic beamformer. Compared to its electrical counterpart, the photonic beamformer has the advantages, such as compactness, light weight, low loss, frequency independence, large instantaneous bandwidth, and inherent immunity to electromagnetic interference [3]. This fact makes the PAA comprising photonic beam former can be a preferable solution for the communication between satellite and aeroplanes.

The goal of beamformer is that the effective radiation pattern of the array is intensified in a desired direction and suppressed in undesired directions [9, 11]. Then, the intensification of the radiation pattern in the desired direction results in the main beam of the array. The direction of the main beam can be steered by properly changing the phase relation between the AE signals. The illustration of the changing direction of the main beam is shown on the Figure 2-1:
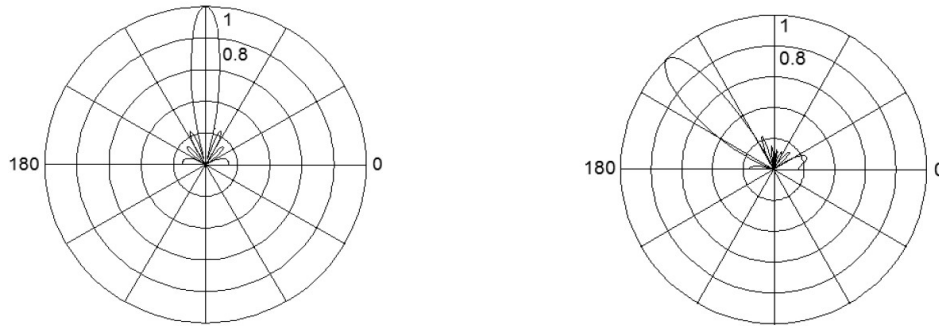

Figure 2-1: Illustration of (left) the main beam of an effective radiation pattern and (right) the beam steering effect. Source: [3]

The simplest PAA is one-dimensional linear array antenna, which is based on gemetry of multiple identical AEs equally spaced along a single line. Although there are various array geometries as explained in [9, 11], to understand the basic principle of PAA, the one-dimensional linear array antenna is sufficient. Figure 2-2 shows the illustration of a simple 4-element linear array antenna.
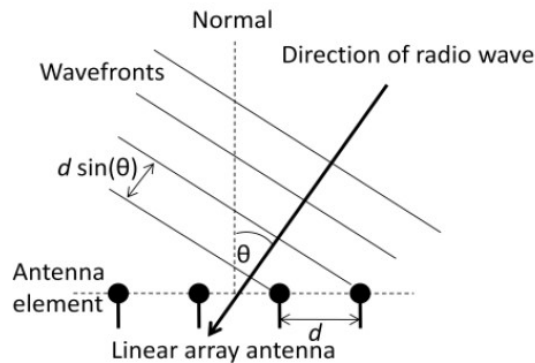

Figure 2-2: Illustration of a 4-element one-dimensional linear array antenna. Source: [3]

Suppose the direction of the radio wave is coming at an angle of θ with respect to perpendicular direction of the surface of the PAA (called normal direction). Then all the spatial points have the same phase form a wavefront which is perpendicular to propagation direction of the wave, and this wavefront will reach each AE at a different time instance. The formula for the difference of the time arrival of the neighboring AE is given as:

$$\Delta t_a(d, \theta) = \frac{d \sin(\theta)}{c_0} \tag{2-1}$$

where d is the spacing between the AEs and c_0 is the speed of light in vacuum. This results in an interelement phase difference:

$$\Delta \varphi(d, \theta, f) = 2\pi f \Delta t_a(d, \theta) \tag{2-2}$$

where f is the frequency of the Radio Frequency (RF) wave.

When this interelement phase difference $\Delta \varphi(d, \theta, f)$ is removed by the additional phase compensation between two neighboring AEs $\Delta \delta = -\Delta \varphi(d, \theta, f)$, the signals from different AEs will be in phase and can be combined coherently. Then after combining the signals the intensification will be achieved for this particular receiving angle θ. The signals coming from a different angle θ' will result in $\Delta \varphi(d, \theta', f)$ which will not be cancelled out by $\Delta \delta$. Then due to the remaining phase difference between the AEs, suppression of the signal will occur after the signal combining of the array. Furthermore, by adjusting the value of $\Delta \delta$, the receiving direction of the array (main beam) can be steered accordingly [3].

Obviously, the application of the PAA in general case will not be as simple as one-dimensional linear array antennas. More complex two-dimensional beam steering is sometimes required for some PAA application. A practical solution of this two-dimensional beam steering is to use a planar array antenna. Basically, it is a rectangular $M \times N$ planar array which can be regarded as M columns of N-element linear arrays or N rows of M-element linear arrays. More formal analyses of PAAs can be found in [9, 11].
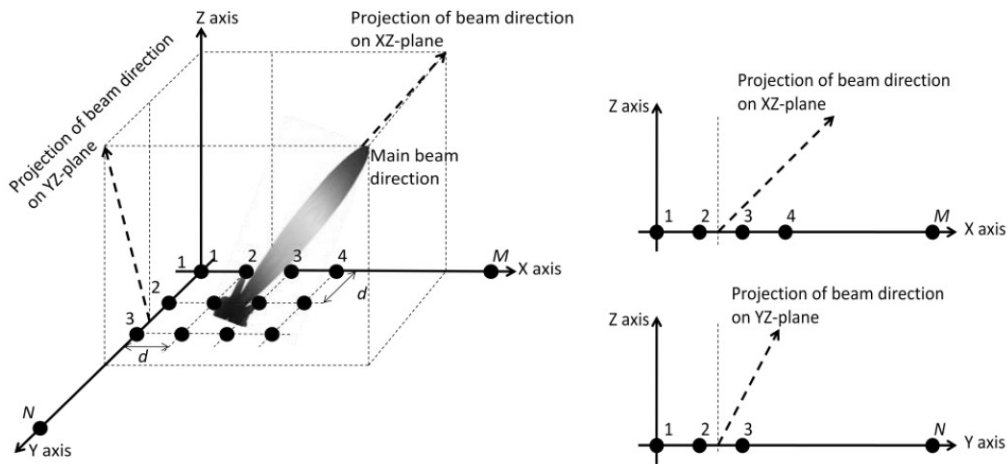

Figure 2-3: Schematic of a rectangular $M \times N$ planar array antenna. Source: [3]

2-2   Optical Ring Resonator

The beamformer which will be considered in this thesis is a photonic beamformer system in which the RF signals received by the AEs are modulated on optical carriers and tunable optical delay lines synchronize the signals modulated on the optical carrier. The Optical Ring Resonator (ORR) is used to implement the tunable optical delay lines. In this section, the principles of ORR will be covered including the structure, the transfer function and transfer matrix used to derive the frequency response of ORRs, and the delay properties of both single and multiple cascaded ORRs.

2-2-1   Structure of the ORR

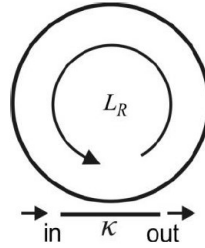A simple one input one output single stage ORR is illustrated on Figure 2-4:

Figure 2-4: Structure of a 1×1 single-stage ORR. Source: [3]

It consists of a ring-shaped waveguide and a straight waveguide. The waveguide are able to couple light between each other. The parameter κ is the power coupling coefficient, which has the value of the range $[0 \cdots 1]$, and L_R is the roundtrip length of ring shaped waveguide. Another parameters are T which is the roundtrip period and ϕ which is the extra phase-shift due to the heater on the top of the ring.

2-2-2   Mathematical Model of the ORR

The behavior of an optical component can be described by its transfer function (or transfer matrix when a component has multiple input/output ports), which relates the amplitude and phase of the field at input to those at output. Rabus [13] and Zhuang [3] have derived the transfer function of which can be summarized as follow.

Derivation of the ORR Transfer Function

To derive the transfer function of an ORR, one can first look at the behavior of its two basic building blocks, namely a waveguide feedback path and a 2 coupler, which are shown in Figure 2-5 (left) and the Z-transform schematic of an ORR is given in Figure 2-5 (right). Let the signal at the right side of the ring be E^r, and the one on the left side be E^l, then one can derive the following relations:
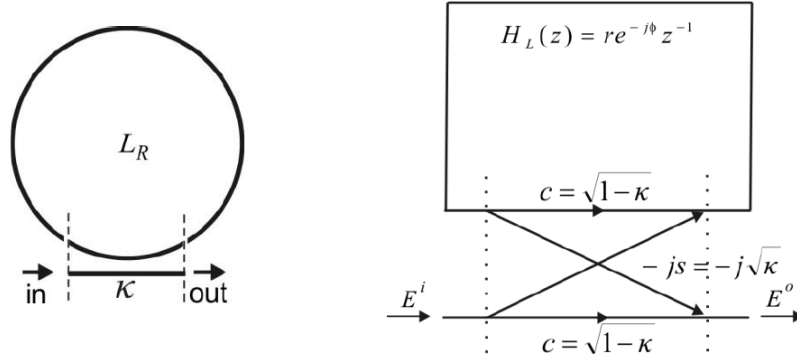
Figure 2-5: (left) An ORR formed by a 2×2 coupler and a feedback waveguide. (right) $Z-$ transform schematic of an ORR. Source: [3]

$$E^r = -j\sqrt{k}E^i + \sqrt{1-\kappa}E^l$$
$$E_l = rz^{-1}e^{j\phi}E^r$$
$$= E_l = rz^{-1}e^{j\phi}(-j\sqrt{k}E^i + \sqrt{1-\kappa}E^l) \tag{2-3}$$
$$= \frac{-j\sqrt{k}rz^{-1}e^{-j\phi}E^i}{1 - r\sqrt{1-\kappa}z^{-1}e^{-j\phi}}$$

$$E^o = \sqrt{1-\kappa}E^i - j\sqrt{\kappa}E^l$$
$$= \frac{\sqrt{1-\kappa}(1 - r\sqrt{1-\kappa}z^{-1}e^{-j\phi})E^i - \kappa rz^{-1}e^{-j\phi}E^i}{1 - r\sqrt{1-\kappa}z^{-1}e^{-j\phi}} \tag{2-4}$$
$$= \frac{\sqrt{1-\kappa} - rz^{-1}e^{-j\phi}}{1 - r\sqrt{1-\kappa}z^{-1}e^{-j\phi}}E^i$$

Substituting $z^{-1} = e^{-2\pi jfT}$ with T the round-trip time of the ring, give the following frequency response:

$$H(f) = \frac{\sqrt{1-\kappa} - re^{-2\pi jfT - j\phi}}{1 - r\sqrt{1-\kappa}e^{-2\pi jfT - j\phi}} \tag{2-5}$$

Derivation of the ORR Phase Response

Principles of Ring Resonator-Based Optical Beamforming Networks

3-1 Optical Beamforming Network Structure

Chapter 4

Deep Learning Neural Network for Tuning the Optical Beamforming Networks

4-1 Section 1

Appendix A

The Back of the Thesis

Appendices are found in the back.

A-1   An Appendix Section

A-1-1   An appendix subsection with C++ Listing

```cpp
//
// C++ Listing Test
//

#include <stdio.h>

for(int i=0;i<10;i++)
{
    cout << "Ok\n";
}
```

A-1-2   A MATLAB listing

```matlab
%
% Comment
%
n=10;
for i=1:n
    disp('Ok');
end
```

Appendix B

Yet Another Appendix

B-1 Test Section (Again?)

Ok, all is well.

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Glossary

List of Acronyms

DCSC   Delft Center for Systems and Control

OBFN   Optical Beamforming Network

ORR   Optical Ring Resonator

AE   Antenna Element

NLP   Non-linear Programming

PAA   Phased Array Antenna

RF   Radio Frequency