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INTEGRATED ANTENNAS AND ANTENNA ARRAYS FOR WIRELESS COMPUTER BOARD-TO-BOARD COMMUNICATION

Michael Jenning

GENEHMIGTE DISSERTATION

zur Erlangung des akademischen Grades

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ABSTRACT

This thesis, as part of the Collaborative Research Center Highly Adaptive Energy-Efficient Computing (HAEC), addresses passive beam-switching networks for the frequency range of 150 GHz to 200 GHz. Multiple possible candidates are theoretically investigated and evaluated. The most suitable choice, the Butler matrix (BM), is further designed and fabricated. This network itself only requires passive components, the switching part is moved to the active frontend circuits. It is achieved by switching on and off the frontends at the individual ports.

The theoretical model of a BM is rather simple. The main challenge is to find a design that is suitable for fabrication and achieves a bandwidth of at least 30 GHz. The designs to be fabricated are demanding in terms of fabrication technology. Accuracy and required resolution are the toughest requirements. Additionally, rather complex structures in terms of geometry also require a very flexible technology regarding allowed topologies.

Having suitable technologies available, the fabricated designs demonstrate the feasibility of the BM approach to achieve beam-switching. Furthermore it is shown that an accurate knowledge of the material's characteristics is required to achieve valid simulation results. This also applies to technology properties like surface roughness or used metals.

Besides the BM, antenna elements are also investigated. Among them are on-chip antennas, which are fabricated in the same technology as the active circuits in another project of HAEC. Because of the low achieved antenna gain, antennas based on technology similar to the one used for the BMs are also designed.

Based on the fabricated BM designs and the designed antennas it is possible to design a complete antenna array that has four distinct beams. Furthermore, eight copies of the BM can be cascaded to design an array that has 16 distinct beams in two spatial dimensions.

ZUSAMMENFASSUNG

Die Dissertation, welche im Rahmen des Sonderforschungsbereichs 912 – Highly Adaptive Energy-Efficient Computing (HAEC) – entstand, widmet sich passiven Netzwerken für umschaltbare Gruppenantennen im Frequenzbereich zwischen 150 GHz und 200 GHz. Zahlreiche geeignete Kandidaten werden theoretisch betrachtet und bewertet. Der vielversprechenste Ansatz, die Butler Matrix (BM), wird weiter vertieft und Schaltungen darauf aufbauend entworfen und gefertigt. Das Netzwerk selbst besteht nur aus passiven Komponenten, der Schaltanteil wird dabei in die aktiven Schaltungen der Endstufe verlagert. Das Umschalten wird dabei durch gezieltes ein- und ausschalten der Endstufen erreicht.

BM als solche haben einen sehr einfachen Aufbau. Die größte Herausforderung besteht dabei darin, ein Entwurf zu finden, der sowohl für die Fertigung geeignet ist und eine Bandbreite von mindestens 30 GHz erreicht. Die zu fertigenden Entwürfe stellen dabei hohe Ansprüche an die Fertigungstechnologie. Sowohl Genauigkeit als auch Auflösung stellen dabei die schärfsten Anforderungen da. Darüber hinaus bedingen die komplexen geometrischen Strukturen eine, in Bezug auf umsetzbare Topologien, flexible Technologie.

Mit der Verfügbarkeit geeigneter Technologien konnte mit gefertigten Entwürfen die grundlegende Funktionalität der BM zum Erreichen des Strahlumschaltung gezeigt werden. Darüber hinaus wird aufgezeigt, dass erst eine genaue Kenntnis der Materialparameter hinreichend genaue Simulationen zulässt. Dies trifft auch auf Parameter der verwendeten Technologie zu, wie z. B. die Rauigkeit oder verwendete Metalle.

Neben den BM werden auch Einzelantennen untersucht. Darunter sind chip-integrierte Antennen, welche in der gleichen Technologie gefertigt werden, die für aktive Schaltungen innerhalb eines weiteren Projekts von HAEC verwendet wird. Bedingt durch die geringen erzielten Antennengewinne werden auch Antennen entworfen, welche in einer ähnliche Technologie gehalten sind, wie die der BM.

Ausgehend von den gefertigten BM und den entworfenen Antennen lassen sich vollständige Gruppenantennen fertigen, welche vier ausgeprägte Hauptstrahlrichtungen haben. Darüber hinaus können acht der BM so mit einander verbunden werden, dass eine Gruppenantenne mit 16 ausgeprägten Hauptstrahlrichtungen in zwei räumlichen Richtungen entsteht.

CONTENTS

1. INTRODUCTION

1.1. MOTIVATION

Today's global connectivity through the Internet with its numerous applications and services requires enormous computing and networking resources. Without any doubt, those requirements are increasing [Cis14a, Cis14b]. To cope with this trend, both computational and networking capabilities have to be addressed. On the computational front, the two most common approaches are (i) increasing the performance of individual cores and (ii) parallelism. The latter is a multi-level approach. Nowadays, central processing units (CPUs) have typically two or four cores. In server computers, up to 16 cores per single CPU are available. The next level is the use of multiple CPUs per node, employing main boards with up to four CPU sockets. Combining multiple of such nodes in one or more racks is the next level of parallelism, resulting in the construction of large data centers or high performance computing (HPC) systems.

Efficiently utilizing the available computational resources requires a tremendous amount of communication within each level and across levels. For the communication within one rack or between multiple racks, cable based technologies like Ethernet, InfiniBand, or optical, e. g., optical Ethernet, are employed or introduced. They all require switching devices and running cables to enable communication between all nodes. Additionally, predictions indicate that the bandwidth per copper based wired link is limited at 20 Gbit/s to 30 Gbit/s or subject to sophisticated equalization efforts to achieve higher data rates [VLS+10, YML+10].

Communication between computer boards is a major issue addressed in the Deutsche Forschungsgemeinschaft funded Collaborative Research Center 912 *Highly Adaptive Energy-Efficient Computing (HAEC)* [SFB] that was initiated at TU Dresden in 2011. One of the goals of the project is the use of wireless links with data rates of up to 100 Gbit/s between two computer boards in a HPC system. This scenario is depicted in Abbildung 1.1. To achieve this goal, wire based interconnects between nodes on different boards are replaced by wireless links. To keep the relative bandwidth at a manageable level, carrier frequencies will be above 100 GHz. Within this thesis, the air-to-circuit interface is investigated: antenna elements and switched beam feeding networks based on a BM.

Considering the usage scenario shown in Abbildung 1.1, it becomes obvious that there is a simplification possible that reduces the complexity of the wireless frontend. After installing the boards on the backplane, their position is fixed. Additionally, the position of each node on a board is fixed. This enables the simplification of utilizing switched beam forming antenna arrays instead of fully flexible beam steering antenna arrays. One network known to enable said usage scenario is the BM.

As discussed in more detail in Kapitel 4, the BM has the drawback of only off-axis beams and is missing a broadside beam. Within the Collaborative Research Center (CRC) it was shown that under this constraint, an optimal placement of the

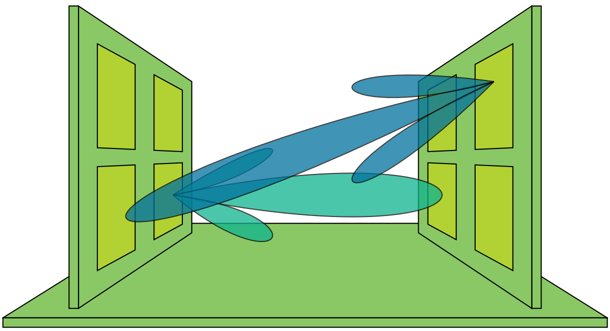

Figure 1.1.: Illustration of a wireless board to board communication scenario in an HPC box. For simplicity, only two boards with four chips each and two possible links are shown. Full flexibility of the links enabled by beam switching is targeted.

chips on neighboring boards exists [IMF+13]. Higher levels in a communication system, e. g. network coding, have to be aware of this characteristic.

1.2. STRUCTURE OF THE THESIS

This thesis consists of six chapters. Kapitel 2 describes the state-of-the-art.

Kapitel 3 presents the investigated antenna elements that are either designed in a semi-conductor process or in a polymer based sequential build-up technology. Included are the design and measurement of fabricated samples. Finally, an evaluation of the antenna elements is given.

Kapitel 4 presents the BM based beam switching network. Two designs are discussed that differ in the number of electrical layers used. The combination of one selected BM switched beam former network and the previously presented antenna elements is extensively discussed in Kapitel 5.

The thesis concludes with a conclusion and outlook on future work.