Beiträge aus der Informationstechnik

Mobile Nachrichtenübertragung
Nr. 105

**Christoph Jans**

# Frequency Dependent Beamforming - A Time Efficient Solution to the Beam Alignment Problem in Millimeter Wave Communications

VOGT

Dresden 2025

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.dnb.de abrufbar.

Bibliographic Information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Zugl.: Dresden, Techn. Univ., Diss., 2025

Die vorliegende Arbeit stimmt mit dem Original der Dissertation „Frequency Dependent Beamforming - A Time Efficient Solution to the Beam Alignment Problem in Millimeter Wave Communications“ von Christoph Jans überein.



Gesetzt vom Autor

ISBN 978-3-95947-080-3

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Niederwaldstr. 36
01277 Dresden
Germany

Phone: +49-(0)351-31403921
Telefax: +49-(0)351-31403918
e-mail: info@vogtverlag.de
Internet : www.vogtverlag.de

Technische Universität Dresden

# Frequency Dependent Beamforming - A Time Efficient Solution to the Beam Alignment Problem in Millimeter Wave Communications


Dipl.-Ing.

**Christoph Jans**


der Fakultät Elektrotechnik und Informationstechnik der Technischen Universität Dresden

zur Erlangung des akademischen Grades

**Doktoringenieur**

(Dr.-Ing.)

genehmigte Dissertation


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Tag der Einreichung: 22.06.2024
Tag der Verteidigung: 16.12.2024

# Abstract

Millimeter-wave frequencies offer a wide spectrum and high data rates, but their use is associated with high propagation losses. These losses can be compensated for by using directional links between the transmitter and the receiver. Beamforming is hereby key to generate array manifolds with maximum energy transfer at each receiver location to improve the quality of the link. However, in conventional systems, e.g., phased arrays, beamforming is associated with consecutive probing of a large number of potential beams from a given analog codebook leading to large signaling overhead. Especially in dense network situations or fast-changing environments, the classical method of *brute force* iterative testing of all potential beams limits the overall performance of the system.

In this thesis, a beamforming network based on *true-time* delays that intentionally violates the so-called narrowband assumption so that the generated beam pattern becomes frequency dependent, is proposed as a promising alternative to classical iterative beamformer training. Compared to the brute-force approach, a hardware implementation based on true-time delays of multiples of the reciprocal of the bandwidth can be used to generate frequency dependent beamformers that simultaneously address all angular directions at different baseband frequencies. We exploit this property and present low-complexity digital signal processing algorithms to both accelerate analog beamformer selection and provide the most accurate angle estimation possible.

Our results will help in highly congested millimeter-wave networks with a large number of users to overcome the limitations of the classical method of iterative beamforming testing as defined in the 801.11ay standard and we will propose a framework which is able to reduce the signaling overhead of orchestrating all user requirements. Link quality and overall network performance can be improved using frequency dependent beamforming, where receivers need only perform a simple spectrum analysis to find their own best analog beamformer or angle of departure estimation. We show

how to select the analog beamformer faster than in the classical brute-force approach and how to estimate the beam angle with a mean absolute error less than $1^\circ$ with low hardware complexity, i.e., array sizes of $M = [8, 16]$ antenna elements. A base station equipped with such a frequency dependent beamforming device assists all receiver selecting their best analog beamformers and, ultimately, helps to maximize the number of active users and data sum-rates. It is interesting to note that increasing the number of antenna elements $M$ does not immediately increase the accuracy of the angle estimation. Only the resolution, i.e., distinguishing two individual paths with almost equal angle of departure can be improved. Hereby, the Rayleigh criterion defines a well known minimum angular resolution for given antenna array physical dimension. Increasing the number of frequency sampling points, however, minimizes the *quantization* error when sampling the power spectrum and, therefore, helps to minimize estimation error.

# Kurzzusammenfassung


Die Nutzung von Millimeterwellenfrequenzen im Bereich der mobilen Datenübertragung wird mit dem Versprechen großer ungenutzter Frequenzbereiche und daraus resultierender hoher Datenraten angepriesen. Ihre Nutzung ist jedoch mit hohen Ausbreitungsverlusten verbunden. Diese Verluste können durch gerichtete Verbindungen zwischen der Basisstation und den Endgeräten der Nutzer reduziert werden. Die Strahlformung ist dabei der Schlüssel, um den „Beam“ gezielt auf den jeweiligen Nutzer auszurichten und die Verbindungsqualität sowie das Link Budget zu verbessern. Bei herkömmlichen Ansätzen mit vielen Antennenelementen, wie z.B. Phased Arrays, ist die Strahlformung jedoch mit einem hohen Signalisierungsaufwand verbunden.

In dieser Arbeit wird ein auf Echtzeitverzögerungen basierendes Strahlformungsnetzwerk vorgestellt und als vielversprechende Alternative zum iterativen *brute-force* Strahlformungstraining vorgeschlagen. Im Vergleich zu diesem herkömmlichen Ansatz, bei dem alle möglichen Strahlformerkombinationen getestet werden, kann durch fest implementierte Echtzeitverzögerungen, die als Vielfaches des Kehrwerts der Bandbreite ausgelegt sind, ein frequenzabhängiger Strahlformer für eine lineare Gruppenantenne erzeugt werden. Eine solche Antenne erlaubt es, alle Strahlrichtungen gleichzeitig mit unterschiedlichen Basisbandfrequenzen anzusprechen. Diese Eigenschaft machen wir uns zunutze und stellen im Folgenden digitale Signalverarbeitungsalgorithmen mit geringer Komplexität vor, um sowohl die Auswahl analoger Strahlformer zu beschleunigen als auch eine möglichst genaue Winkelschätzung durchzuführen.

In stark ausgelasteten Millimeterwellen-Netzwerken und bei einer großen Anzahl von Nutzern führt die klassische Methode des iterativen Strahlformungstests, wie sie im 801.11ay-Standard definiert ist, zu einem erheblichen Signalisierungs-Overhead. Die daraus resultierende erhöhte Komplexität bei der Orchestrierung aller Nutzeranforderungen, um die starken Interferenzen zwischen den einzelnen Nutzern zu reduzieren, stellt eine große

Hürde für die Nutzung von Millimeterwellen für die mobile Datenübertragung dar. Mit Hilfe der frequenzabhängigen Strahlformung zur schnellen Detektion möglicher Übertragungsrichtungen und Strahlformer kann die Linkqualität für jeden Nutzer schnell bestimmt und damit die Gesamtleistung des Netzes verbessert werden. Die Entscheidung wird dabei auf Basis einer einfachen Spektrumanalyse bzw. daraus abgeleiteten Winkelschätzungen getroffen. In dieser Arbeit wird sowohl gezeigt, wie die Auswahl des analogen Strahlformers schneller als mit dem klassischen Brute-Force-Ansatz erfolgen kann, als auch eine Möglichkeit, den Abstrahlwinkel mit einem mittleren absoluten Fehler kleiner $1^\circ$ bei geringem Hardwareaufwand und Arraygrößen von $M = [8, 16]$ zu schätzen. Das Hauptaugenmerk dieser Arbeit liegt auf der Verwendung eines frequenzabhängigen Beamformers, der sendeseitig eingesetzt die Auswahl analoger Beamformer stark vereinfacht und letztendlich eine Maximierung der Anzahl aktiver Nutzer bei gegebenen Ratenanforderungen bzw. eine Verbesserung der Gesamtleistung des Systems erreicht. Interessant ist hier, dass durch die alleinige Erhöhung der Anzahl der Antennenelemente keine Erhöhung der Winkelschätzungsgenauigkeit erhalten wird. Lediglich die Auflösung, d.h. die Unterscheidung von zwei Einzelpfaden mit annähernd gleichem Abstrahl-/Empfangswinkel kann verbessert werden. Dabei definiert das Rayleigh-Kriterium eine bekannte Mindestwinkelauflösung für eine Antennengeometrie. Die Erhöhung der Anzahl der Frequenzabtastpunkte minimiert jedoch den Quantisierungsfehler bei der Abtastung des Leistungsspektrums und trägt somit zur Minimierung des Schätzfehlers bei.

# Acknowledgement

I am grateful to my supervisor, Prof. Dr. Gerhard Fettweis, for his unwavering support and invaluable guidance during my doctoral studies. His mentorship has been instrumental in shaping my academic pursuits, and I am deeply grateful for his continuous encouragement.

My sincere gratitude extends to Dr. Wolfgang Rave and Dr. Meik Dörpinghaus, my respected group leaders, whose expertise and engaging discussions have significantly enriched my research experience. Their mentorship and dedication have inspired me to remain curious and to explore my field of research.

My time at the Vodafone Chair for Mobile Communication has been truly fulfilling, thanks to the collaborative spirit and fellowship among my colleagues. I am deeply appreciative of the contributions of Dr. Martin Schlüter, Dr. Peter Neuhaus, Dr. Xioahang Song, Dr. Richard Jacobs, Stephan Zeitz, Dr. Mostafa Kahlili-Marandi, and Torge Mewes. Their support, guidance, and intellectual exchange have played a pivotal role in my growth as a researcher.

Furthermore, I am grateful to the Technical University of Dresden, the DFG, and the BMBF for their generous financial support, which has enabled me to pursue my research goals and contribute to the advancement of knowledge in the field of mobile communications.

Finally, I would like to express my sincere gratitude to my family. Thank you for your assistance and understanding throughout this journey. Your consistent support has been instrumental in my research success and I am deeply indebted to you all for believing in me and standing by my side every step of the way.

# List of Abbreviations

**2G** Second Generation. 1

**3G** Third Generation. 1

**4G** Fourth Generation. 1

**5G** Fifth Generation. 2

**6G** Sixth Generation. 2

**AoA** Angle of Arrival. 5

**AoD** Angle of Departure. xviii, 5, 7, 9, 16–18, 21, 22, 40, 43, 44, 49, 54, 61, 69, 70, 72, 75, 77–80, 82–85

**AR** Augmentend Reality. 2, 3, 11

**BA** Beam Alignment. 6, 8

**BFN** Beamforming Network. 4, 5, 19, 32, 33, 38

**BS** Base Station. xvii, xviii, 7, 13–18, 31, 59, 66

**CSI** Channel State Information. 53–56

**DFT** Discrete Fourier Transform. 28

**EIRP** Effective Isotropic Radiated Power. 8

**ES** Exhaustive Search. xix, 6–8, 29, 49, 50, 53–57, 61, 62, 64–66

**FDB** Frequency Dependent Beamforming. xix, 7–9, 12, 54–57, 61, 62, 64–66

**G** Generation. 1

**GRLT** Generalized Likelihood Ratio Test. 63, 64

**HS** Hierarchical Search. 6

**iDFT** Inverse discrete Fourier Transform. 60

**IoT** Internet of Things. 2, 11

**LHS** Left-hand Side. 35, 36

**LMMSE** Linear Minimum Mean Squared Error. xix, xx, 73–77, 79–81, 84, 92, 95

**LOS** Line of Sight. 9, 16, 57, 65, 80

**LTE** Long Term Evolution. 2

**LTI** Linear Time-Invariant. 19, 33, 38

**MIMO** Multi-Input Multi-Output. 4, 11, 12, 29

**MMSE** Minimum Mean Squared Error. 69

**mmWave** Millimeter Wave. xviii, 2, 3, 6, 8, 9, 11–18, 22, 24, 29, 33, 38, 43, 47, 50, 55, 56, 61, 66, 83–85

**MSE** Mean Squared Error. xx, 94

**MU** Multi User. 9

**MUSIC** MUltiple SIgnal Classification. 69, 79

**NLOS** Non-Line of Sight. 3, 16

**OFDM** Orthogonal Frequency Division Modulation. xx, 12, 38, 50, 51, 54–57, 72, 75, 94

**PCB** Printed Circuit Board. 3

**RF** Radio Frequency. xvii, 4–6, 44, 45, 51, 84

**RHS** Right-hand Side. 35, 36

**RMSE** Root Mean Squared Error. xix, xx, 72–76, 81

**RX** Receiver. xvii, 3–7, 9, 21, 38, 39, 50, 51, 55, 85

**SINR** Signal to Interference and Noise Ratio. 15

**SNR** Signal to Noise Ratio. xix, xx, 8, 9, 49, 53, 56, 61, 62, 64–66, 71–73, 76, 77, 79–81, 94

**THz** Tera Hertz. 11

**TX** Transmitter. 3, 4, 6, 7, 9, 13, 21, 85

**UE** User Equipment. xvii, xviii, 7, 13–18, 20, 31, 49, 66, 67, 69, 82, 92, 93

**ULA** Uniform Linear Array. xviii, 17, 18, 27, 33, 40, 43, 44, 57, 61, 66, 71

**URA** Uniform Rectangular Array. xix, 43–45

**VR** Virtual Reality. 2, 3, 11

# List of Publications

Parts of this thesis have been published in the following peer-reviewed articles

- X. Song, **C. Jans**, L. Landau, D. Cvetkovski and G. Fettweis, "A 60GHz LOS MIMO Backhaul Design Combining Spatial Multiplexing and Beamforming for a 100Gbps Throughput," 2015 IEEE Global Communications Conference (GLOBECOM), San Diego, CA, USA, 2015, pp. 1-6, doi: 10.1109/GLOCOM.2015.7417737.

- **C. Jans**, X. Song, W. Rave and G. Fettweis, "Frequency-Selective Analog Beam Probing for Millimeter Wave Communication Systems," 2020 IEEE Wireless Communications and Networking Conference (WCNC), Seoul, Korea (South), 2020, pp. 1-6, doi: 10.1109/WCNC45663.2020.9120815.

- W. Rave and **C. Jans**, "On the Mapping between Steering Direction and Frequency of a Uniform Linear Array with Fixed True Time Delays," WSA 2020; 24th International ITG Workshop on Smart Antennas, Hamburg, Germany, 2020, pp. 1-6.

- M. Khalili Marandi, **C. Jans**, W. Rave and G. Fettweis, "Evaluation of Detection Accuracy and Efficiency of Considered Beam Alignment Strategies for mmWave Massive MIMO Systems," 2021 55th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2021, pp. 664-671, doi: 10.1109/IEEECONF53345.2021.9723262.

- **C. Jans**, X. Song, W. Rave and G. Fettweis, "Fast Beam Alignment through Simultaneous Beam Steering and Power Spectrum Estimation Using a Frequency Scanning Array," WSA 2020; 24th International ITG Workshop on Smart Antennas, Hamburg, Germany, 2020, pp. 1-6.

- P. Neuhaus, M. Schlüter, **C. Jans**, M. Dörpinghaus and G. Fettweis, "Enabling Energy-Efficient Tbit/s Communications by 1-Bit Quantization and Oversampling," 2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Porto, Portugal, 2021, pp. 84-89, doi: 10.1109/EuCNC/6GSummit51104.2021.9482427.

- **C. Jans**, W. Rave and G. Fettweis, "Fast Beam Alignment Via True Time Delay Frequency Dependent Beamforming Using Fixed and Variable Length Tests," 2022 IEEE International Symposium on Phased Array Systems & Technology (PAST), Waltham, MA, USA, 2022, pp. 1-7, doi: 10.1109/PAST49659.2022.9975036.

- **C. Jans**, M. Dörpinghaus and G. Fettweis, "Schalkwijk and Kailath feedback coding with sequential decision-making," 2017 IEEE 17th International Conference on Ubiquitous Wireless Broadband (ICUWB), Salamanca, Spain, 2017, pp. 1-5, doi: 10.1109/ICUWB.2017.8250993.

# Contents

# List of Figures

# 1 Introduction

Mobile communications technology has revolutionized our daily lives over the past 30 years, allowing us to connect and access vital services anywhere in the world, anytime. Today, 9% of the world's population is connected to a mobile network and 55% uses the mobile internet [@GSM22]. Connectivity affects the way we work, play, live, learn and do business.

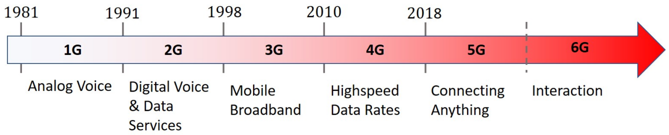


**Fig. 1.1.:** From 1G to 5G and beyond: Evolution of mobile wireless communication standards

Since the 1980s (see Fig. 1.1), wireless communication has been gaining popularity through various generations (G) of mobile communication. All started with analog voice telephony in the 1980s, which was then replaced by the second generation (2G) in the 1990s by its more efficient digital implementation of voice telephony. When wireless voice communication was accessible, but data communication was limited to short text messages, E-mails, and/or simple web-based services, it was clear that bringing data communication to the users was the next big step forward. As a result, mobile data transmission kicked off the evolution of the third generation 3G in the 2000s. This was the first time consumers experienced the mobile internet through handheld devices, and smartphones entered the market, replacing more and more traditional feature phones. For example, the first iPhone was introduced in 2007 focusing the consumer market. The lack of a keyboard and the introduction of a large touchable display foreshadowed the developments of mobile communications for the next decade as being more consumer orientated. Therefore, the fourth generation (4G) network in 2010, finally addressed issues in energy efficiency and network coverage problems and a wider spectrum of consumers entered the market due to enhanced system capacity and user experience. As a consequence smartphones finally rose out of their niche. *Real* wireless internet experience without any limitation was obtained and the development of the so-called Long Term Evolution (LTE) based 4G network finally allowed a large variety of applications. The working field relied on higher availability of their employees using video calls, E-mails, and messenger services. Enhancements for private users concerned the usage of smartphones for online gaming, music/video streaming and social media or networking.

With the current fifth generation (5G) on the roll-out and its even higher demands on energy efficiency, system capacity, reduced latency, and data rates, mobile operators addressed industry needs especially in the field of Internet of Things (IoT) and robotics, and only partially the consumer market when it comes to increased data rates. New applications w.r.t. wireless remote controls, collaborative robotics, and augmented/virtual reality (AR/VR) applications are going to revolutionize sectors like health, agriculture, construction, and logistics. As business/professional users have been again the first mover for the current 5G standard, the next generation, sixth generation, (6G) may be again consumer oriented. Therefore, an infrastructure to enable a Personal Tactile Internet is envisioned [FB21; Zha+19]. Furthermore, communication & sensing need to be thought together as well as access to control and orchestration of several remote robotic functions over mobile communication networks are key. The type of applications may vary from home assistants to AR/VR, Industry 4.0, health care, and so on. Apart from the harsh restrictions on latency, low packet error rate, and improvements on jitter to enable the above-mentioned 5G/6G applications, overall demand for higher data rates in the order of $100\,\mathrm{Gbit/sec}$ and above exists especially in the field of AR/VR and may only be satisfied by allocating more and more bandwidth. This amount of bandwidth, however, is not available in the common sub $6\,\mathrm{GHz}$ regime and operators need to switch to the licensed & unlicensed frequencies in the millimeter-wave (mmWave) regime and above for reliable data communication.

## 1.1 Problem Statement

From future applications such as self-driving cars, AR/VR, or remote collaborative robots [FB21; And+14; Zha+19], we may infer the need for higher data rates as well as low latency. However, the practical implementation and digital signal processing needed to fulfill those demands are still not fully understood. Escaping to higher carrier frequencies may at first sound like a reasonable approach, but comes at the price of severe path losses with adversarial effects on the link budget [Akd+14; Bal+15; Bar+15] and requires controlled energy distribution through analog/digital or hybrid beamforming, which we will discuss briefly in the following.

The problem at hand is the less robust mobile communication system at those carrier frequencies, which is highly dependent on detrimental environmental effects such as scatterers, non-line of sight (NLOS) events, fading, shadowing, movements, and other channel variations. While common communication systems rely on sector/cell-based coverage and almost *isotropically* radiation of energy, we know from [YBC19; Mar+21; NZL17] that path losses in the mmWave regime are severe and can only be compensated for by highly directional antennas on the transmitter (TX) and/or receiver (RX) side. There are several hardware implementations to obtain highly directional antennas, which we will not go into detail in this work; however, for further reading, see [Jan+19; RTY16; Tre02; Men+16]. In our investigation, we assume hardware implementations where antenna arrays are built from an integrated process directly on the printed circuit board (PCB) connected to the analog front-end [AB07; Jan+19]. We know from [Hea+16; Han+15; Bal+15], that more and more antenna elements, or patches, can be integrated into the same area or form factor as the distance of neighboring antenna elements shrinks with the increase of the carrier frequency. With this, highly directional antenna arrays can be built in hardware and an overall antenna gain linearly scaled by the number of used antenna elements can be obtained. Due to the path loss at higher frequencies and *anisotropical* radiation of energy, the actual wireless channel between any TX and RX can be well described by a ray-tracing geometrical channel [JR18], where only a few paths reflected by a small number of scatterers contribute to the overall receive energy. Under this assumption, it is critical that the TX is focusing all its energy on those limited number of paths and the RX is capturing all energy from these paths. A solution to this problem has to be found during the synchronization and channel estimation phase. One can directly see that in addition to all the synchronization and estimation challenges of wireless communications, we inherently introduced a new challenging *spatial* problem of finding optimal energy transfer between TX and RX. In general, this spatial problem is tackled by either one of the three beamforming concepts that are commonly denoted as *digital*, *analog*, and *hybrid* beamforming. The characteristically properties and the differences among these methods may be summarized as follows:

- Digital beamforming (see Fig. 1.2): Allowing to design different signals per antenna element in digital baseband. The RF chain consists of an analog-to-digital/digital-to-analog converter, up/down frequency mixer, passband filters, and power amplifiers such as a low-noise amplifier. The full benefit of spatial multiplexing is available at the cost of higher hardware complexity and digital signal processing overhead. Such a costly approach is often assumed to be impractical due to power consumption and lack of heat dissipation in the integrated design. Estimating for each TX and RX antenna element pair its complex channel gain produces a high-dimensional channel state matrix, which is also often intractable. However, research and development into an all-digital solution for massive MIMO communication systems is an active research topic in both academia and industry.

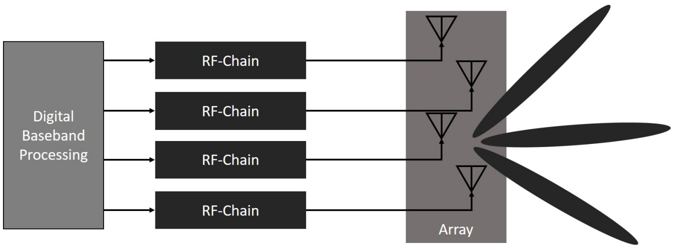


**Fig. 1.2.:** Digital beamforming: The number of RF chains equal to the number of antenna elements, allowing full flexibility and multiple beams simultaneously

- Analog beamforming (see Fig. 1.3): One RF-chain is connected to a *beamforming network* (BFN) which is connected to all antenna elements.

The BFN is made up of a set of phase shifters (also known as phased arrays [YBC19; Hea+16; Baj+19; RTY16]) or time delays per antenna element, which allows the main lobe of a beam of an antenna array to be orientated in a certain direction. Hereby, the challenge is to steer the main lobe of the beam towards the angle of arrival (AoA) or angle of departure (AoD) of the best path to maximize the energy transfer. Typically, we restrict the problem to a finite set of pre-defined phase shifters or true time delays and formulate an analog orthogonal *codebook*. Common hardware implementations of such preconfigured BFNs are, e.g., a Butler-matrix [BL61; NZL17] or Rotman-Lens [RTY16]. These are low-cost solutions but does not allow different beamforming weights to be applied for various receivers, as only a single beam can be generated at a time. No spatial multiplexing for multi-user scenarios is possible.

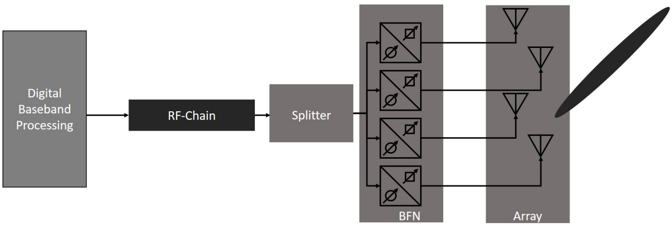


**Fig. 1.3.:** Analog beamforming: One RF chain may serve one RX since it creates only one beam at a time. A common hardware implementation using fixed phase shifts is the so-called Butler matrix.

- Hybrid beamforming (see Fig. 1.4): Last, we can combine analog and digital beamforming. This means, we use the BFN from the analog beamforming but allow a finite number of RF chains to digitally pre-process the data stream transmitted over different beam patterns in baseband. The signaling overhead is hereby reduced, as in the first step we try to find appropriate analog beamformers and then, in the second step, find digital complex weights to optimally combine these analog beamformers. The digital processing takes place in a (much) lower dimensional vector space and can be solved more easily [Chi+18; Chi+17]. It was shown that for the common assumptions of a sparse geometrical mmWave channel, the rate loss using hybrid beamforming compared to digital beamforming is negligible [Chi+17; Han+15].

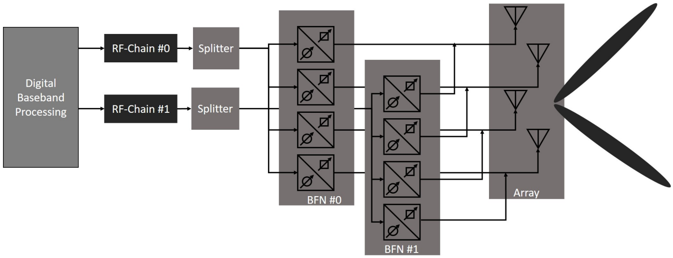


**Fig. 1.4.:** Hybrid beamforming: Trade-off between digital and analog beamforming; Limited amount of RF-chains creating multiple beams at most the number of RF chains simultaneously

In the present thesis, we focus our investigation on analog beamformer selection from a given analog codebook. Therefore, we give a solution to the problem *beam alignment* (BA) from the literature [NZL17; Bar+15; Bar+16b; SHC19; Alk+17]. Under BA, we understand finding these beamformers from a given analog codebook, which are optimal w.r.t. to their energy coupling.

## 1.2 Motivation

Solving this BA problem in a time-efficient manner is the main goal of the present thesis. To better understand this, one has to know that finding the best optimal beamformer from a given codebook is often implemented by a consecutive scheme, for example *exhaustive search* (ES). This scheme is a brute force method that tests all possible combinations from the codebook of TX and/or RX to find the pair which maximizes the energy transfer. By design, this scheme is optimal in the sense of always finding the best combination in the presence of no noise and/or no interference. Also in [Mar+21] it was shown that an exhaustive search needs less observations to decide in favor of a beamformer in the presence of noise than a *hierarchical search* (HS) or a *compressed sensing* approach under a strict equal transmit power constraint.

But still, observing that ES also tests non-promising beamformers from the analog codebook the following question arises:

> "Can we find a faster beam alignment scheme than exhaustive search to select beams of a very large codebook used for millimeter wave communication?"

The answer to this question that we present in this thesis is to reuse the idea of a *frequency scanning array* from radar [DJ79] and propose a *frequency dependent beamforming* scheme that is able to reduce the number of needed observations and, therefore, increases the overall time efficiency of the beam alignment phase. Frequency dependent beamforming (FDB) will be used in downlink beamformer training mode. The underlying concept may be thought of as instantaneous *beam sweeping*, meaning that we concurrently address the complete angular domain with our pilot signal. Hereby, each baseband frequency is mapped to a specific angle of departure (AoD). One can think of a lighthouse, however, instead of mapping each angle to *time* as it is done in a classical lighthouse, we map each frequency of the pilot spectrum to a given angle. Furthermore, such a downlink-based beamformer training has a great advantage in that a base station (BS) or TX can broadcast a certain training sequence using FDB and each user equipment (UE) or RX can randomly start to receive the training sequence. With this, each UE may asynchronously receive the pilot broadcast signal; however, we will show that still all UEs are able to infer favorable beamformers or the AoD.

A quick dive into the details of the approach immediately shows the potential benefit of FDB. For example, for $M_{TX}$ beamformers at the transmitter and $M_{RX}$ beamformers at the receiver, ES needs to try at least $M_{TX}M_{RX}$ combinations and depending on the actual noise realizations collects $N_{ES}$ samples per combination to achieve a given performance criterion. That means $M_{TX}M_{RX}N_{ES}$ samples in total are processed. However, using frequency dependent beamforming at the TX in downlink broadcasting mode, where all angles are excited with different frequencies, only the receiver now has to test its own selection of beamformers from the codebook. Here, $N_{FDB}$ samples are collected for each $M_{RX}$ beamformer to fulfill a given performance metric (e.g. minimizing the error of false detection), i.e. a total of $N_{FDB}M_{RX}$ samples are processed. Now, the first advantage of FDB is that the transmitter does not switch between different beamformers, which reduces the hardware requirements of the beamformer network. Especially when we design a communication system where the base station is equipped with a large antenna array, i.e., $M_{TX} \geq 100$ and above. Instead of constantly switching the beamformer, we can continuously send a pilot signal that excites the environment with the specific angle- and frequency dependent signature. Second, whenever $N_{FDB} \leq M_{TX}N_{ES}$, frequency dependent beamforming is fundamentally more time efficient than exhaustive search. Of course, $N_{FDB}$ dependents also on the actual SNR measured at the receiver. Since only a fraction of the bandwidth is captured by the receiver, it can be argued that sharing bandwidth (FDB) or time (ES) is a zero-sum game, which is not true, as we will show in the following chapters.

Minor remark: Not included in this work, but worth mentioning, is that standard-compliant transmitters in the field must meet the effective isotropic radiated power (EIRP) constraint. Since the EIRP measures the power density of an antenna for a given direction of maximum signal power, i.e., the power transfer along its main lobe direction, we can increase for FDB the total transmit power of the antenna array compared to ES as the power and bandwidth are spread over a wide angular range. However, this effect is not further investigated in this thesis as even without exploiting EIRP standardization constraint, we will show that our proposed downlink broadcasting beam alignment scheme based on FDB is more time efficient and allows beam alignment in challenging scenarios with short coherence times and/or varying environments.

Also not included in this work but potentially promising direction for future research involves localization algorithms that utilize channel impulse responses obtained from regular frequency independent beam steering within mmWave communication systems [Sed+21; Vas+23]. Inspired by the principles of bistatic radar systems, the communication link can serve a dual purpose, facilitating both data transmission and radar functionalities within a joint communication and sensing scenario [FB21]. Improvements could be achieved by employing beamforming techniques such as frequency dependent beamforming. Scatterer detection by simple spectrum analysis at the receiver side using FDB together with antenna pattern deconvolution [Sed+23] and two-way ranging measurements [Sar+19] may produce high resolution scatterer maps of the surrounding environment and reveals the position of each receiver in field.

## 1.3 Main Contributions and Outline

Within this work, a time-efficient solution to the challenging BA problem occurring in mmWave communications is given by applying the concept of frequency dependent beamforming (FDB). Most previous works on beam alignment (BA) in mmWave communication systems focus either on multi-level codebooks [NZL17; Mar+21], compressed sensing techniques [CZW18; CZW19; Hea+16; SHC19; Wan+21], or on improving and accelerating the exhaustive search method [MRF19; DPW17; Bar+14]. All these schemes have in common that a rough time/frame synchronization has to be done first. Therefore, pilot sequences with good auto-correlation and cross-correlation properties are used but often neglected when evaluating the time efficiency. Since we have to assume that beam alignment is the very first operation between transmitter (TX) and receiver (RX), all these signaling overheads occur in a very low signal to noise ratio (SNR) domain. In this work, we consider the use of a separate additional hardware component at the TX that uses a frequency dependent beamforming (FDB) network to excite the environment. With this, we show a significant speed-up in finding optimal analog beamformers from a given codebook (see Chapter 4) as well as a minimal mean absolute angle estimation error of less than $1^\circ$ (see Chapter 5). We extend current research on frequency dependent beamforming by applying results from fixed and variable-length tests known from accelerating exhaustive search tests [Mar+21; MRF19; Bar+14]. In the context of angle estimation, we propose a linear minimum mean square interpolation technique, an easy correlator based approach, and a super-resolution method for minimal mean absolute angle estimation error.

The thesis is organized as follows: In Chapter 2, we specify the problem at hand and describe the initial access, the geometric mmWave channel, and the true time delay beamforming which we will link to the classical *frequency independent beamforming*. We focus our investigation on downlink beamforming training, as this is more time-efficient than uplink beamforming training, especially for multi-user (MU) scenarios. In Chapter 3, we adapt the system model derived in Chapter 2 and introduce frequency dependent beamforming. By adding a constant fixed true-time delay of the reciprocal of the bandwidth, or by using frequency offsets of multiples of the reciprocal of the total symbol duration, a bijective mapping between the full angular domain and the frequency bandwidth is obtained [RJ20]. In Chapter 4, frequency dependent beamforming is used to study the optimal selection of an analog beamformer from the well-known *orthogonal* analog beamforming codebook. We compare the results with the optimal scheme, i.e., exhaustive search, using a fixed-length test and a variable-length test [JRF22] and prove the time efficiency and reduced signaling overhead for frequency dependent beamforming. Chapter 5 explains the approach of estimating the angle of departure (AoD) of the line-of-sight (LOS) path. With accurate AoD information, the base station can select its beamformers accordingly and optimally weight the individual analog beamformers in hybrid beamforming scenarios. Finally, in Chapter 6, we summarize the main results and give an outlook on possible future investigations. Noteworthy similar research is done by [YBC19; Bol+20; BC22; BSC22]. However, their focus does not lie on the time efficiency of the scheme and more on the actual implementation of the hardware. Moreover, they only use the concept of frequency dependent beamforming using true time delays at the receiver side. So our focus on time-efficiency in this work is still an open question and will be answered in the following.

## 1.4 Notations

Normal font letters represent scalar quantities, while vectors and matrices are denoted by bold lower-case and bold upper-case letters, respectively. The element in $i$th row and $j$th column of matrix $\mathbf{A}$ is denoted by $[\mathbf{A}]_{\mathrm{i,j}}$. Hermitian, transpose, or conjugate of a variable are denoted by $(.)^H$, $(.)^T$, and $(.)^*$. $|.|^2$ is the element-wise calculation of the absolute-squared value of a vector or matrix. The operator diag$(\mathbf{a})$ or diag$(\mathbf{A})$ creates a matrix with diagonal entries of vector $\mathbf{a}$ or selects only the diagonal entries of a matrix $\mathbf{A}$, respectively. $\mathcal{R}(x)$ and $\mathcal{I}(x)$ are the real and imaginary part of $x$.