



Bile Peng

# **Advanced Antenna Technologies Based on Channel Characterization for Future Terahertz Communications**



**Technische  
Universität  
Braunschweig**



Institut für Nachrichtentechnik

# ADVANCED ANTENNA TECHNOLOGIES BASED ON CHANNEL CHARACTERIZATION FOR FUTURE TERAHERTZ COMMUNICATIONS

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We may have knowledge of the  
past but cannot control it; we  
may control the future but have  
no knowledge of it.

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Claude Elwood Shannon  
(1916 - 2001)

The dilemma raised by the father of information theory still remains at the center of the communication technology after more than half of a century and is especially challenging for the future terahertz (THz) communications. In the years at Institut für Nachrichtentechnik (Institute for Communications Technology), TU Braunschweig, I dedicated myself to the problems of knowledge (estimation) and control (processing) of THz channel and signal, in order to bring this promising concept one step further to the reality.

I would like to express my gratitude to my supervisor Prof. Dr.-Ing. Thomas Kürner, who gave the opportunity to undertake the dissertation to a student not from the faculty of electronic engineering. This unusual decision helped me to step into the communication technology research community. In the following years, I always appreciate his expertise and kindness. His instruction, encouragement and the open working atmosphere in our department are the best things that a young scholar can expect. It was a great experience to work with and to learn from him.

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Braunschweig, March 2018

*Bile Peng*

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## Abstract

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The terahertz (THz) communication utilizes the frequency resource beyond 300 GHz and is considered as a promising solution to the future indoor multi-gigabit data transmission due to the huge available bandwidth (up to 50 GHz). The latest development of the semiconductor technology and diverse demonstrators show that the THz communication is not only a long term vision, but can be an actual breakthrough in the upcoming years.

However, the so far realized THz demonstrators only work in relatively simple scenarios, where the wireless channels are stationary. The objective of this dissertation is to apply the THz communication to wireless personal area network (WPAN) and wireless local area network (WLAN), where the wireless channel is characterized by rich multipath components (MPC) and dynamics, with the aid of advanced antenna technologies. In particular, we consider *angle of arrival (AoA) estimation for adaptive directive antennas and precoding and detection for broadband massive multiple-input-multiple-output (MIMO)*.

The performance of the considered antenna technologies depends largely on the channel characteristics. Therefore, the dissertation begins with channel measurement with vector network analyzer (VNA), channel sounder (CS) and channel modeling with ray-tracing and ray-launching simulations in the considered application scenarios. The simulation results are compared with and calibrated according to the measurement results. A new method based on the Hungarian algorithm and space alternating generalized expectation-maximization (SAGE) algorithm is developed to calibrate the electromagnetic parameters of materials. Based on the comprehensive channel measurement and simulation results, the most important characteristics of the THz channels are summarized for the design and justification of the later introduced algorithms.

The AoA estimation is required for the application of adaptive directive antennas. However, a trivial beam searching process is considered impractical due to its time consumption. Various researches show that the spatial distribution of propagation paths at different frequency ranges are similar. Based on this observation, a two-phase AoA estimation algorithm is proposed. In the first phase, the AoA is roughly estimated with a low frequency (say, 5 GHz); In the second phase, the precise AoA estimation is carried out at the THz range within the range defined in the first phase. In this way, the precise AoA

can be estimated within a short period of time.

Furthermore, the dynamic AoA estimation problem is considered, where the user equipment (UE) is moving during the data transmission. Since the AoA change is temporally correlated (because the human movement shows certain statistical patterns), a finite-memory-based hidden Markov model (HMM) is applied to describe the AoA change along time and the forward-backward algorithm is applied for the AoA estimation. In addition, if there are several access point (AP) antennas, the AoA changes at different AP antennas are spatially correlated because all the AoA changes are due to the same UE displacement. This spatial correlation can be presented in an extended probabilistic graphical model and be utilized with belief propagation to further improve the estimation precision.

Besides the directive antenna, massive MIMO is another promising antenna technology to realize high antenna gain and reduce interference. In this dissertation, the massive MIMO precoding and detection problems for single carrier broadband channel with delay dispersion is addressed. The block matrix is used to describe the distortion effect of the channel on the transmitted signal. The power-constraint downlink precoding problem is solved with the Lagrange multiplier and the uplink detection coefficients are obtained with the orthogonality principle. The least square least square QR (LSQR) algorithm is applied to efficiently solve the optimization problem in real time. Simulation results show that a good system performance is achieved with reasonable computational effort.

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## Kurzfassung

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Die Terahertz (THz)-Kommunikation verwendet die Frequenzressourcen über 300 GHz und ist aufgrund der großen verfügbaren Bandbreite (bis zu 50 GHz) eine vielversprechende Lösung zur zukünftigen Indoor Multi-Gigabit-Datenübertragung. Die jüngste Entwicklung der Halbleitertechnik und verschiedene Demonstratoren zeigen, dass die THz-Kommunikation nicht ein langfristiges Ziel, sondern ein tatsächlicher Durchbruch in den nächsten Jahren sein kann.

Die bislang realisierten Demonstratoren und Prototypen funktionieren allerdings nur in relativ einfachen Szenarien, in denen die Funkkanäle stationär sind. Das Ziel dieser Dissertation ist, die THz-Kommunikation für zukünftige Indoor Wireless Personal Area Network (WPAN) und Wireless Local Area Network (WLAN), bei der der Funkkanal durch Mehrwegausbreitung und Dynamik (die Empfängerposition ist unbekannt und häufig nicht stationär) zu charakterisieren ist, mithilfe von fortgeschrittenen Antennentechniken, nämlich die *Ankunftswinkelschätzung für adaptive Richtantennen* und *Vorcodierung und Erkennung von breitbandigem Massive Multiple-Input-Multiple-Output (MIMO)*, zu ermöglichen.

Die Performance der untersuchten Antennentechniken hängt weitgehend von der Eigenschaft des Funkkanals ab. Deswegen werden zuerst Kanalmessung mittels Vector Network Analyzer (VNA), Channel Sounder (CS) und anschließend Kanalmodellierung mit Ray-Tracing- und Ray-Launching-Simulationen in den betrachteten Anwendungsszenarien durchgeführt. Die Simulationsergebnisse werden mit den Messdaten verglichen und kalibriert. Eine neue Space Alternating Generalized Expectation-Maximization (SAGE)-Algorithmus basierende Methode wird beschrieben, um die elektromagnetischen Parameter der Materialien zu kalibrieren. Basierend auf den umfangreichen Mess- und Simulationsergebnissen werden die wichtigsten Eigenschaften des Funkkanals für das Design und die Rechtfertigung der vorgeschlagenen Algorithmen zusammengefasst.

Die Ankunftswinkelschätzung ist eine Voraussetzung für die Anwendung von adaptiven Richtantennen. Für eine präzise Schätzung ist allerdings eine lange Laufzeit erforderlich, die das Verfahren unpraktisch macht. Verschiedene Forschungsergebnisse zeigen, dass die räumlichen Verteilungen der Ausbreitungswege bei hohen und niedrigen Frequenzen

ähnlich sind. Darauf basierend wird ein zweiphasiger Algorithmus zur Ankunftsschätzung entwickelt. In der ersten Phase wird der Winkel bei einer niedrigen Frequenz (z. B. 5 GHz) grob geschätzt und in der zweiten Phase wird der genaue Winkel innerhalb des Bereichs, der in der ersten Phase bestimmt worden ist, bei der THz-Frequenz geschätzt. Auf diese Weise kann der genaue Winkel in einer kurzen Zeit gefunden werden.

Des Weiteren wird das Problem der dynamischen Ankunftswinkelschätzung diskutiert, bei der sich das Nutzergerät während der Datenübertragung bewegt. Da die Ankunftswinkelveränderung zeitlich korreliert ist (da die menschliche Bewegung bestimmte statistische Muster aufweist), wird ein gedächtnisbasiertes Hidden Markov Model (HMM) zur Darstellung der Ankunftswinkelveränderung angewendet. Der Forward-Backward Algorithmus wird dann zur bayerischen Schlussfolgerung benutzt, um die Schätzungs-genauigkeit zu verbessern. Wenn es mehrere Access Point (AP)-Antennen gibt, sind die Ankunftswinkelveränderungen bei unterschiedlichen AP-Antennen räumlich korreliert, weil die Veränderungen von derselben Nutzergerätbewegung verursacht sind. Diese räumliche Korrelation kann in einem erweiterten probabilistischen grafischen Modell dargestellt und mit Belief Propagation ausgenutzt werden, um die Schätzungsgenauigkeit weiter zu verbessern.

Schließlich wird das Problem der Vorcodierung und Erkennung vom Massive MIMO untersucht, welches neben der Richtantenne auch eine vielversprechende Lösung für hohen Antennengewinn und niedrige Interferenz ist. In dieser Dissertation wird ein Algorithmus zur Vorcodierung und Erkennung für den breitbandigen, frequenzselektiven Funkkanal entwickelt. Für die Vorcodierung im Downlink wird der Lagrange-Multiplikator verwendet, um unter der Leistungsbedingung die Codierungskoeffizienten zu optimieren. Für die Erkennung im Uplink wird der optimale Erkennungskoeffizienten nach dem Orthogonalitätsprinzip berechnet. Die Blockmatrix wird zur Beschreibung der Signalübertragung angewendet und der Least Square QR (LSQR)-Algorithmus wird für eine effiziente Lösung des Problems verwendet. Die Simulationsergebnisse zeigen, dass eine gute Performance mit mäßigen Rechenaufwand erreicht werden kann.

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