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Superresolution Time Delay Estimation for Joint Communication and Sensing Systems

Dipl.-Ing.

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der Fakultät Elektrotechnik und Informationstechnik der
Technischen Universität Dresden

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Superresolution Time Delay Estimation for Joint Communication and Sensing Systems
Dissertation

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Abstract

Conventional design of wireless communication systems has primarily focused on enhancing data transmission performance, such as increasing throughput, reducing latency, and improving system reliability. Recent developments have not only continued to advance these core metrics but have also expanded to incorporate new features and services beyond communication. One particularly attractive service is sensing, which is motivated by its ability to exploit the information contained in the received signal for various applications, such as intruder detection, people flow monitoring, and indoor localization, apart from its potential contribution to communication performance. This leads to the concept of joint communication and sensing (JCAS) design. In addition to data transmission, a JCAS system aims to retrieve environmental information from all possible propagation paths. An essential aspect of JCAS design is the integration of sensing capabilities into existing communication systems without significant hardware modifications.

One of the important information that can be extracted from received signals is the propagation delays from the transmitter to the receiver via multiple paths. These delays are associated with distances, and thus, can be utilized for ranging and localization. However, the resolution and accuracy of time delay estimation using conventional algorithms, such as cross-correlation, are constrained by signal bandwidth. This limitation often restricts their usage in existing communication systems, especially within the sub-6 GHz spectrum.

The objective of this work is to explore and develop algorithms that can relax bandwidth requirements while still providing reasonable resolution and accuracy, considering practical applicability in realistic scenarios. Specifically, this work focuses on subspace-based superresolution time delay estimation algorithms and proposes several enhancements. These enhancements include the flexible utilization of frequency resources for sensing, extensions that

significantly increase resolution, and approaches that reduce computational complexity. The effectiveness of the proposed methodologies, in terms of estimation accuracy and resolution compared to state-of-the-art solutions, is evaluated through numerical simulations and further verified with realistic setups. In particular, the experiments are focused on ranging applications, utilizing real-world hardware components and channel conditions, demonstrating both the feasibility and the performance gains of the proposed algorithms.

Kurzfassung

Die klassische Entwicklung im Bereich der drahtlosen Kommunikationssysteme hat sich vor allem auf die Verbesserung der Datenübertragung konzentriert, insbesondere auf die Erhöhung des Datendurchsatzes, die Verringerung der Latenz, und die Verbesserung der Zuverlässigkeit. Die aktuellen Entwicklungen zielen nicht nur auf die weitere Verbesserung dieser Kernmetriken ab, sondern auch auf die Erweiterung neuer Funktionen und Dienste über die Kommunikation hinaus. Ein besonders attraktiver Dienst ist das Sensing, das abgesehen von seinem potenziellen Beitrag zu einer verbesserten Datenübertragung durch die Möglichkeit motiviert ist, die im empfangenen Signal beinhalteten Informationen für verschiedene Anwendungen zu nutzen, zum Beispiel für die Erkennung von unbefugtem Zutritt, die Überwachung von Menschenströmen, und die Indoor-Lokalisierung. Dies führt zu dem Konzept des joint communication and sensing (JCAS)-Designs. Zusätzlich zur Datenübertragung strebt ein JCAS-System an, Umgebungsinformationen von allen möglichen Ausbreitungswegen zu erhalten. Ein wichtiger Aspekt des JCAS-Designs ist die Integration vom Sensing in bestehende Kommunikationssysteme ohne wesentliche Hardwareänderungen.

Eine der wichtigsten Informationen, die sich aus den empfangenen Signalen extrahieren lassen, sind die Signallaufzeiten vom Sender zum Empfänger entlang der verschiedenen Pfade. Diese Laufzeiten sind mit Entfernungen verknüpft und können daher zur Abstandmessung und Lokalisierung verwendet werden. Die Auflösung und Genauigkeit der Laufzeitschätzung durch traditionelle Algorithmen, wie zum Beispiel die Kreuzkorrelation, ist jedoch durch die Signalbandbreite begrenzt. Diese Einschränkung verhindert die Anwendung dieser Algorithmen in bestehenden Kommunikationssystemen, insbesondere im Sub-6 GHz-Spektrum.

Das Ziel dieser Arbeit ist es, Algorithmen zu untersuchen und zu entwickeln, die die Anforderungen an die Bandbreite verringern und dennoch eine angemessene Auflösung und Genauigkeit bieten, wobei die praktische Anwendbarkeit in realistischen Anwendungsfällen berücksichtigt wird. Konkret konzentriert sich diese Arbeit auf Algorithmen zur Schätzung der Zeitverzögerung auf der Grundlage von Signalunterräumen und entwickelt mehrere Erweiterungen. Zu diesen Erweiterungen gehören die flexible Nutzung von Frequenzressourcen für das Sensing, Erweiterungen, die die Auflösung signifikant erhöhen, und Ansätze, die die Rechenkomplexität reduzieren. Die Performance der vorgestellten Methoden in Bezug auf Schätzgenauigkeit und Auflösung im Vergleich zum Stand der Technik wird durch numerische Simulationen evaluiert und mit realistischen Messungen verifiziert. Die Experimente fokussieren insbesondere auf Ranging-Anwendungen unter Verwendung realer Hardwarekomponenten und Kanalbedingungen, um sowohl die Umsetzbarkeit als auch den Performancegewinn der vorgestellten Algorithmen zu veranschaulichen.

Acknowledgement

Time flies. When I first arrived in Dresden in 2013, I never imagined that I would go through such a journey. It was a cloudy rainy autumn day, even slightly blue. After spending some time learning the language, I attended my very first lecture at TU Dresden. It was the Vorlesung Nachrichtentechnik (Communications Engineering in German) since I had studied this subject in my bachelor's and was curious to see how it is taught here. That lecture marked the beginning of my journey, and even then, I had a strong feeling that I wanted to work with the professor teaching it. That professor turned out to be my doctoral father, Prof. Gerhard Fettweis.

I wish my language skills were good enough to fully express my gratitude to him for giving me the opportunity to have such a unique and enriching experience. It was a journey filled with knowledge, skills, joy, frustration, stress, discipline, valuable lessons, and above all, the optimism to pursue my goals without fear of failure. These are the things I will carry with me for the rest of my life: to stay curious and optimistic about the future.

With this opportunity, I would also like to express my heartfelt thanks to my former colleagues and mentors: Dr. Martin Danneberg, who supervised my first student job at the chair. With Martin, I learned how far theory can sometimes be from reality. Prof. Norman Franchi guided me through project management. Beyond that he demonstrated to me how to face difficult moments with persistent positiveness and passion. Dr. Ahmad Nimr, my dear Habibi, who supervised all of my publications and with whom I went through so many challenging moments. Dr. Philipp Schulz, who is always calm and never hesitate a second to offer his help. Dr. Roberto Bomfin, from whom I drew much inspiration. Dr. Ivo Bizon, with whom I had many fruitful discussions, shared both frustrations and joyful moments. Friedrich

Burmeister, with whom I truly experienced the beauty of cooperation. Daniel Swist, who absolutely showed me what "just do it" can mean in practice.

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My deepest gratitude never ends going to my parents and my beloved wife, who have always been there for me, supporting me with relentless strength. No matter how far I go, I always know there is a light for me, even in the darkest night.

This thesis was made possible by all of you, and it is dedicated to all of you.

Contents

1

Introduction

1.1 Motivation

The development of wireless communication technologies has passed through a long journey. Now, it has reached the era of the fifth-generation mobile network (5G), and developments on the sixth-generation mobile network (6G) have already started. It begins with analog modulations, which support only basic voice transmissions with poor data rates but make the first step towards mobile connectivity. As the technology evolves, a shift towards digital processing brings improved spectrum efficiency and additional services such as short message service (SMS) and multimedia messaging service (MMS). Thereafter, advancements in modulation and coding schemes further increase data rates, providing mobile internet access and video calling, thereby significantly enhancing network capabilities and services. From then on, the progress has focused on achieving higher data rates, reducing latency, and improving reliability. These advancements support various applications and allow emerging technologies like autonomous driving and augmented reality [PRG+18; BNL+21; SPLY21].

Moving toward the next generation of wireless communications systems, the concept of joint communication and sensing (JCAS) has drawn much attention [LCM+22; CBMD23]. JCAS focuses on the joint design of communications and sensing functionalities. Compared with the communications-centric design, it has an extra objective of retrieving information about the propagation environment from the received signal. These environmental information can be, for instance, treated as prior knowledge on the receiver or transmitter side for enhancing channel estimation and prediction, and it is beneficial in improving reliability and reducing overhead. Moreover, compared with the radar-centric design, JCAS systems exploit the communications signal designated for data transmission or channel estimation to perform sensing without requiring additional resources or hardware components. In this manner, sensing functionalities can be seamlessly integrated into the existing infrastructure of the communications systems.

Besides improving the communications performance, the integrated sensing capability can also be exploited to provide additional services such as indoor localization. In the context of outdoor positioning, global navigation satelite system (GNSS) is the most recognized system, which can provide centimeter-level accuracy in open areas [CCF+20]. The GNSS system determines user position by utilizing multiple time-of-flight (ToF) estimates, representing the distances between the user and several satellites. However, GNSS positioning poses a significant performance degradation in complex environments, such as densely built cities where skyscrapers abound. In such settings, environmental structures act as reflectors and diffractors, causing multipath propagation that significantly distorts ToF estimation [MLNW01; SSLJ13]. This issue becomes even more pronounced in indoor scenarios, where non-line-of-sight (NLOS) components are considerably more prominent and frequently even dominant. With the influence of NLOS paths, methods such as cross-correlation (CCR) or matched filtering for ToF estimation demonstrate poor accuracy and resolution. These methods mainly focus on the amplitude of correlation results and neglect phase information. As a result, the overall performance is significantly dependent on the signal bandwidth.

There are several approaches to mitigating the constrained accuracy caused by NLOS paths, with the most straightforward being the extension of signal bandwidth, which enhances both resolution and accuracy. However, the bandwidth is an exceptionally costly resource, especially in the sub-6 GHz spectrum for communications systems. The conventional communication systems are commonly designed with relatively smaller bandwidths, sufficient to meet communication objectives. Typically, the bandwidth per channel is 20 MHz for technologies like 2.4 GHz wireless local area network (WLAN) [RC22], long term evolution (LTE) [Joh12], or standard 5G [Joh19]. The bandwidth can be expanded to 100 MHz in 5G campus networks [Ind20], which are local area networks. With the current WLAN standard on 6 GHz, the aggregated bandwidth can reach up to 320 MHz [KLA20; RC22]. Furthermore, the ultra-wideband (UWB) technology offers a wideband solution, but its transmit power is bounded, restricting it to short-range applications only [CSL+22]. In addition, in indoor scenarios, the availability of line-of-sight (LOS) cannot be guaranteed. Consequently, replicating a GNSS approach for indoor scenarios is impractical, as it relies solely on the ToF of the LOS component.

Alternatively, several studies demonstrate that position information is not exclusively contained within the LOS path. Rather than treating NLOS components as interference and focusing exclusively on LOS ToF estimation, it is possible to utilize these paths to extract valuable position information instead of simply attempting to eliminate them [WML+16; GMU+16; GJW+16; GKW+20; WS22]. However, these approaches require a significantly higher resolution in path delay estimation, which becomes impractical in the sub-6 GHz spectrum when relying on CCR or matched filtering based delay estimation methods.

To address the issue of resolution being limited by signal bandwidth, superresolution methods have been proposed. The term *superresolution* indicates that it is possible to achieve time resolution beyond the sampling interval (under high signal-to-noise ratio (SNR) assumption), thereby exceeding the delay estimation resolution limits imposed by signal bandwidth. Fig. 1.1 illustrates an example demonstrating the benefits of superresolution methods. Note that the parameters selected for the simulation presented in Fig. 1.1 serve as examples only. An extensive statistical evaluation is detailed later in this work in Section 4.5.

It is observed that with the CCR approach, resolving paths with delay differences smaller than the sampling interval is not possible. In contrast, the employed superresolution method provides two distinct peaks that accurately align with the actual path delays. Unlike the CCR or matched filtering approaches, which focus only on the amplitude of the correlation results, superresolution methods also consider the phases and the structure of the underlying signal model and, therefore, can resolve beyond the boundaries of the sampling frequency at the receiver. These methods exploit the frequency-domain channel estimates and assume that these estimates consist of a linear combination of a few base vectors, each corresponding to different propagation paths, and extract channel parameters based on this model.

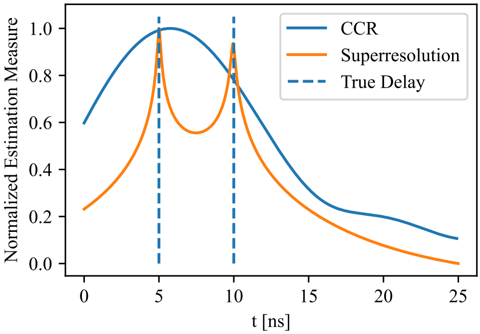

Fig. 1.1.: Comparison of CCR-based and the superresolution approaches for path delay estimation, where the path delay difference is smaller than the sampling interval, path gains: $[0.88, 0.47]$, and path delays: $[5, 10]$ns, carrier frequency: 3.75 GHz, bandwidth: 100 MHz, SNR: 20 dB.

Some methods achieve this using an iterative approach, such as the space-alternating generalized expectation-maximization (SAGE) algorithm [FTH+99]. This algorithm fine-tunes the parameters of several base vectors in an iterative manner and approximates the frequency-domain channel samples by linearly combining these vectors while minimizing a defined log-likelihood function. Alternatively, this approximation can be performed by a compressive sensing method known as atomic norm minimization (ANM) [BTR13], which minimizes the defined atomic norm and utilizes a dual polynomial to retrieve the parameters. However, both SAGE and ANM are not efficient in practical systems due to their high computational complexity. Although they can provide stable estimations when paths are well-separated, even in low SNR conditions, their accuracy and resolution significantly decrease when the paths are closely located.

As further candidates, subspace-based superresolution methods enjoy the linear structure of the frequency-domain channel samples and employ singular value decomposition (SVD) or eigendecomposition (EVD) to derive orthogonal base vectors spanning both the signal- and noise-subspaces. These methods achieve improved resolution by benefiting from the orthogonality of these base vectors. Nevertheless, subspace-based methods rely on the assumption of a linear structure, which may not accurately reflect the reality considering the radio frequency (RF) hardware impairments in practical systems. Moreover, although the subspace-based methods have great potential, their estimation performance often needs further improvement. Additionally, the computational complexity is another significant challenge, limiting subspace-based superresolution path delay estimation (SPDE) methods in practical applications. On the one hand, to enhance the estimation performance of the subspace-based SPDE, it is beneficial to use longer reference sequences, as this directly leads to a higher processing SNR. However, an extended reference sequence significantly increases computational complexity. For instance, in subspace-based methods, computational complexity approximately increases cubicly with the reference sequence length.

Motivated by the potential of delay estimation in sensing applications, this work aims to exploit techniques that address the limitations of state-of-the-art solutions. It focuses on developing a superresolution multipath channel path delay estimation method for JCAS systems. This method is designed to provide enhanced resolution for sensing applications with limited frequency resources and constrained computational complexity, and its effectiveness is verified through practical experiments.

1.2 Contributions and Outline of This Work

The contributions and outline of this work are listed as follows:

- **Chapter 2** provides an overview of wireless channel models. It starts with the characteristics of electromagnetic waves and their propagation mechanisms. Building on this foundation, it emphasizes the importance of ray-tracing-based channel modeling for the numerical evaluations of sensing algorithms. Furthermore, it proposes a low-complexity image-based multipath channel simulator that incorporates multipath components caused by reflections from walls surrounding the transmitter and receiver. The proposed channel simulator and the results are published in [ZBdA+21].
- **Chapter 3** defines the signal model used in this work and showcases the estimation objectives. In addition, it details three related path delay estimation methodologies: an iterative expectation maximization (EM) approach,

a compressive sensing approach, and the subspace-based approaches. These three related state-of-the-art approaches are employed as benchmarks for the evaluation presented in Chapter 4.

- **Chapter 4** proposes several enhancements to the existing subspace-based methods. It begins with a flexible formulation for the path delay estimation (PDE) matrix, which is required for subspace identification. This formulation outlines the utilization of frequency-domain channel estimates and sets the foundation for further extensions. Building on this, the multi-band SPDE is introduced, which combines frequency resources from disjoint frequency bands. Moreover, it is demonstrated that, even with channel estimates from a single frequency band, their complex conjugate counterparts can be mathematically conceptualized as samples from a virtual-band. Thus, the concatenation of both represents a multi-band system, which improves the delay estimation resolution significantly. In addition, the approach to reducing computational complexity is explored, along with the potential for applying frequency-domain filters. Besides, the evaluations through numerical simulations are presented. The proposed methodologies and their evaluation results are published in [ZNSF22a; ZNSF23a; ZNSF23b; ZNSF22b; ZNSF24a; ZNSF24b].

- **Chapter 5** depicts the evaluations conducted using practical hardware components under realistic environmental conditions. This chapter includes the software implementation for an automated measurement framework and the performance evaluation with controlled channels. In addition, the proposed methodology is utilized in two ranging setups to verify its performance; the first employs an outdoor two-way ranging (TWR) setup in the sub-6 GHz spectrum, and the second utilizes a 26 GHz mmWave mono-static ranging setup in indoor scenarios. The results are published in [ZNSF23a; BZNF22; ZNS+23; ZNS+24].

- Finally, **Chapter 6** concludes this work and provides directions for further research.

In addition to the publications mentioned above, the author has published [ZNF19] as the first author and co-authored in [BZS+22; dAZN+22; NZCF20; DBN+20a; DZK+19].