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Ubiquitous Radio Sensing

Localization of Non-Cooperative Users

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Abstract

Many applications in the emerging smart environments, such as smart cities and intelligent transportation, require an accurate situational awareness, i.e., information about presence and location of all users in the environment. For example, situational awareness enables location-aware home control, assistive health, or vehicular safety applications. A reliable situational awareness is based on robust communications and sensing techniques, as well as large-scale deployment with respect to the application environment. This demand for both communications and sensing capabilities has recently led to significant research interests in merging the two technologies allowing for an efficient use of spectral resources and a beneficial mutual assistance. An integration of sensing functionality is envisioned as a native capability of next generation wireless networks. The deployment of these perceptive wireless networks ultimately offers the prospect of ubiquitous radio sensing.

Ubiquitous radio sensing allows, in particular, the localization of non-cooperative users. In this context, non-cooperative users are defined as users who are neither equipped with a communications device nor with a dedicated localization device. State-of-the-art algorithms on localizing non-cooperative users typically obtain the required location information exclusively from directly scattered or reflected signals. Further signal components resulting from multipath propagation, for example due to reflections from the surrounding environment, are considered as interfering signals, i.e., clutter, and are suppressed by the receiver.

In this thesis, we propose to exploit the full potential of signal propagation, including multipath, for the localization of non-cooperative users. Therefore, we first provide detailed insights into time-based radio sensing. We derive, develop, and implement the fundamental performance bounds, clutter mitigation techniques, as well as parameter estimation and tracking algorithms to localize non-cooperative users. Moreover, we provide a novel radio sensing approach, referred to as multipath-enhanced device-free localization (MDFL), which complements time-based radio sensing. Instead of mitigating signal components, MDFL makes use of the spatial information contained in the corresponding propagation paths to localize non-cooperative users.

For localization, MDFL exploits user-induced variations in the received power of the individual signal components. These signal components include besides the line-of-sight also multipath components. For realizing this novel sensing approach, we develop corresponding measurement models relating the user-induced variations in the received power of the individual signal components to the user's location. Based on these measurement models, we derive the fundamental performance bounds for MDFL. Finally, we present a Bayesian formulation of the sensing problem and implement corresponding non-parametric filter solutions for MDFL, which are successfully applied to measurement data. To the best of the author's knowledge, this is the first time it is shown that variations in the power of multipath components can be used for the localization of non-cooperative users. Due to its low computational complexity, the proposed MDFL approach represents a suitable technique for the emerging perceptive wireless networks and can help to enable ubiquitous radio sensing.

Contents

Acknowledgements **iii**

Abstract **v**

1 Introduction **1**
1.1 Historical Evolution of Radio Technologies 1
1.2 Ubiquitous Radio Sensing 4
1.3 Contribution of Thesis 6
1.4 Structure of Thesis 7

2 Radio Propagation **9**
2.1 Radio Channel 10
2.1.1 Fundamental Propagation Mechanisms 10
2.1.2 User's Impact on Radio Propagation 13
2.1.3 Deterministic Description of the Radio Channel 16
2.2 Radio Channel Parameter Estimation 17
2.2.1 Signal Model 18
2.2.2 Parameter Estimation 19

3 Radio Sensing **23**
3.1 Radio Sensing Networks 23
3.1.1 Mode of Operation 24
3.1.2 Sensing Signal 25
3.1.3 Topology and Coverage 30
3.2 Radio Sensing Strategies 31
3.2.1 Time-Based Radio Sensing 32
3.2.2 Received Signal Strength-Based Radio Sensing 33
3.2.3 Recursive Bayesian Estimation for User Tracking 35

3.3 Geometric Implications of Multipath Channels 38
3.3.1 Virtual Nodes and Reflection Points 39
3.3.2 Geometric Properties of Single-Bounce Reflections 41

4 Measurement Data **45**
4.1 Measurement Equipment 45
4.1.1 Wideband Channel Sounder 46
4.1.2 Ultra-Wideband Transceiver 47
4.2 Measurement Campaigns 49
4.2.1 Setup I: Apron Environment 49
4.2.2 Setup II: Urban Intersection Environment 51
4.2.3 Setup III: Indoor Environment 53

5 Time-Based Radio Sensing **55**
5.1 Location Estimation Using Delay Estimates 55
5.1.1 Calibration Period 57
5.1.2 Estimation Period 57
5.1.3 Tracking Period 58
5.2 Theoretical Performance Evaluation 60
5.2.1 Cramér-Rao Lower Bound on Location Estimation 60
5.2.2 Posterior Cramér-Rao Lower Bound for Nonlinear Sequential Bayesian Estimation 61
5.2.3 Numerical Results 62
5.3 Measurement-Based Performance Evaluation 68

6 Multipath-Enhanced Device-Free Localization **71**
6.1 Fundamentals of Multipath-Enhanced Device-Free Localization 72
6.1.1 Network and Propagation Model 72
6.1.2 Network Initialization 73
6.1.3 Parameter Estimation 74
6.1.4 Bayesian Multipath-Enhanced Device-Free Localization 75
6.2 Fading Models for Multipath Components 76
6.2.1 Physical Diffraction-Based Model 77
6.2.2 Empirical Exponential Model 82
6.3 Reflection Point Estimation 87
6.3.1 Problem Formulation 88
6.3.2 Elliptic Probability Density Function 89
6.3.3 Sequential Bayesian Estimation of Reflection Point 90

6.3.4 Experimental Evaluation 92
6.4 Theoretical Performance Evaluation 96
6.4.1 Performance Limits to Localization Accuracy 96
6.4.2 Simulation-Based Evaluation of Bayesian MDFL 100
6.5 Measurement-Based Performance Evaluation 109

7 Conclusion and Future Research **113**
7.1 Concluding Remarks and Summary 113
7.2 Main Contributions 115
7.3 Implications for Future Research 116

A Derivation of Elliptic Normal Distribution **119**

List of Abbreviations **121**

Notation and Lists of Symbols **125**
Notation 125
List of Latin Symbols 126
List of Greek Symbols 131

List of Author's Publications **133**
First Author 133
Co-Author 134

References **137**

Chapter 1

Introduction

1.1 Historical Evolution of Radio Technologies

The very origin of any modern wireless technology can be traced back to James Clerk Maxwell's seminal work on electromagnetism in the 1860s. Maxwell predicted the existence of electromagnetic waves, which was confirmed experimentally more than twenty years later by Heinrich Hertz transferring radio waves from a transmitter to a receiver. With his experiments, Hertz further demonstrated characteristic properties of radio waves, including reflection from metallic objects and refraction through dielectric media. These fundamental findings led to a number of pioneering inventions in the early 20th century. Guglielmo Marconi, for example, used radio waves for the wireless transmission of telegraph messages over long distances. With the successful transmission of the first wireless transatlantic message in 1901, he pioneered the commercial use of radio wave technology and firmly established *wireless communications*. Besides carrying information, it was soon found that the propagation properties of radio waves can be also used for obtaining information themselves. In order to prevent collisions between ships, Christian Hülsmeyer developed a device, the so-called telemobiloscope, which was able to detect the presence of other ships in its vicinity. Therefore, the telemobiloscope included a transmitter and a receiver placed directly adjacent to each other. For detection, Hülsmeyer made use of radio waves reflected from distant metallic objects, such as ships as in this particular case. With his patent specification from 1904, he is thus considered the inventor of radar technology, which is today primarily associated with *radio sensing*. The term radar is derived from the acronym of radio detection and ranging and was coined only years later in [nat43]. For radar, ranging refers to the process of radio-based distance measurement between the sensing device and the targeted object. Since that distance directly depends on the location of the targeted

object, Hülsmeyer's invention already illustrates the importance of location awareness for safety applications.

During the first half of the 20th century, the demand for location awareness was primarily driven by maritime and aviation applications, such as route planning or assisting pilots in approach and landing maneuvers. For the timely provision of the required location information, the first navigation systems were developed that exploit the propagation properties of radio waves between distant transmitting and receiving devices for localization. Examples such as the Gee and the long range navigation (LORAN) system, which entered service in 1942 and 1943, respectively, are among the earliest representatives of *radio navigation*. For global deployment, however, these terrestrial radio navigation systems are challenging not only because of immense infrastructure requirements, but also in terms of localization accuracy due to the propagation conditions along the earth's surface [SDM14]. Overcoming these accuracy and coverage limitations, global navigation satellite systems (GNSSs) were developed beginning in the 1960s. The Transit system provided the first operational GNSS service from 1964, but it took until 1994, that with the global positioning system (GPS) a fully global navigation service was available. With the release of GPS for civil use in 2000 and the launch of further GNSSs such as the European Galileo system, radio-based localization became fully established as a service and the basis for a wide range of location-aware applications.

By the end of the 20th century, advances in semiconductor technology and the accompanying digitization enabled the widespread deployment of wireless communications systems, triggering an entire wireless revolution [Rap91]. While designed primarily for information transmission, these wireless communications systems can also be used for localization purposes, providing the ability to sustain dedicated radio navigation services [WLW09, SDM14]. Especially in GNSS-denied environments, such as in urban canyons and indoors, the majority of current radio localization systems exploit the local wireless communications infrastructure, including base stations (BSs) of cellular communications systems [KCPW21], access points (APs) of wireless local area networks (WLANs) [KGA17], and short range radio communications systems like ultra-wideband (UWB) [WS02, SW10]. Regardless of the underlying infrastructure, any radio navigation system requires users to carry devices for localization. In the following, we therefore refer to cooperative users, when users are equipped with devices that are capable of transmitting or receiving radio signals. Hence, along with the proliferation of smartphones and other wearable devices with wireless communications capabilities, the localization of these devices became almost synonymous with the localization of the corresponding cooperative users.

But not all users are permanently equipped with any of the aforementioned devices. Thus, these users can neither communicate nor determine their own location and are therefore considered as non-cooperative. However, information about presence and location of users for the purpose of situational awareness is essential for many applications in the emerging smart environments, such as smart cities and intelligent transportation [CLJM21]. Specifically, reliable and comprehensive situational awareness enables a variety of advanced use cases, such as location-aware home control, assistive health, or vehicular safety applications [CLJM21]. Situational awareness, in turn, requires robust communications and sensing techniques, as well as a large-scale deployment with respect to the application environment. The Internet of Things (IoT), which combines the functionalities of sensing and communications within a modular architecture [AFGM+15], might represent a suitable option for achieving such situational awareness. Within the concept of the IoT, the localization of non-cooperative users can be realized through a distributed and connected network of sensing devices. For example, for vehicular safety applications, the required situational awareness can be achieved through the deployment of commercially available sensors, like acoustic [MA04], vision-based [ST13], or dedicated radar sensors [MPC+08], that detect and localize road users. The sensing capabilities of the individual technologies differ and are challenged by different physical properties. While acoustic sensors are basically susceptible to ambient noise and surrounding sound interference, vision-based sensors like cameras exhibit limited performance in adverse lighting conditions and often raise privacy concerns. Although limited in imaging resolution, radio sensing technologies, such as radar, offer fundamental advantages in terms of sensing range, susceptibility to environmental conditions, and also privacy. However, beyond remaining technical challenges, one of the biggest impediments to any dedicated sensing technology is its large-scale deployment. Due to the physically constrained coverage areas of individual sensors, a large-scale deployment causes high infrastructure costs. To stay with the example of vehicular safety applications, the realization of seamless, precise, and reliable monitoring of road users would require a huge number of dedicated sensors and, thus, immense, even prohibitive deployment and maintenance costs. Although this example illustrates the limitations of the current IoT, it is the rapidly growing number of connected devices and the accompanying exchange of wireless communications signals that may provide new opportunities for sensing.

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