1 Introduction

Ubiquitous connectivity has become normal in this technology-driven, fast-changing modern world, where we chase from one screen to another. However, the fundamental principle behind all this, electromagnetic waves, is relatively new historically. One quickly forgets that not even 200 years ago, the propagation of electromagnetic waves was unknown. While various effects of electromagnetism were discovered by famous scientists such as Coulomb, Faraday, and Ampere in the late 18th and early 19th century, a compact form of the relationships had yet to be developed. In the 1860s, Maxwell evolved an early form of the wave equation and came to the conclusion „that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws“ [1]. The common form of the Maxwell equations was later formulated by Oliver Heaviside [2]. Heinrich Hertz and his experiments in the late 1880s [3] provided the proof of the Maxwell equations.

Around the turn of the 19th and 20th centuries, Guglielmo Marconi and Ferdinand Braun established the first radio communications, for which they later won the Nobel prize in physics [4, 5]. At the same time, Christian Hülsmeyer found out that metallic objects reflect electromagnetic waves, whereby they can be detected. He named his invention „Telemobiloskop“ and showed it to the public in 1904 in Cologne, Germany, detecting ships [6]. Although his patent did not attract much interest then, his work is the first implementation of a rudimentary radar and laid the foundation for future developments.

The first use of radar was of a military nature, especially before and during World War II. However, later, other areas of application, such as weather radar and the automotive sector, were developed. In the 1960s, A.L. Merlo from the Bendix Corporation published a work about a radar system to avoid collisions [7]. In the course of developments over the next few decades, the frequencies of automotive radar, starting from 10 GHz, quickly rose to the nowadays standard of 77 GHz [8]. In particular, the development of highly integrated chips and the use of microstrip antennas led to reduced costs, making it possible to use radar in almost all vehicles available today. Additionally, with the increased number of channels, angle determination was possible.

While automotive radar was initially used as an auxiliary sensor to avoid collisions, the trend is towards increasingly autonomous vehicles. Alongside other sensors such as cameras or lidars, radars have a decisive advantage in difficult environments such as rain or fog. While optical systems operate in or close to the visible spectrum, they suffer under the same conditions as our eyes. Due to the very different frequencies of radar devices, they can „see“ through fog, although the signal also experiences additional losses. Therefore, it is an essential sensor for autonomous features in the automotive field. Current radars for long-range operation offer 300 m visible range [9, 10, 11] or even up to 530 m [12].

However, one of the most significant disadvantages of radar is the limited angular resolution. Objects at great distances cannot be separated if the angular resolution is too coarse. Two objects at a distance of 300 m on a typical German highway are only 3.5 m or 0.67° apart, which is a challenge because the angular resolution must be even finer, especially for objects of different sizes. The main factor determining angular resolution is the aperture size of the antenna. While a single sensor can not be arbitrarily large, multiple small sensors may overcome this limitation and allow huge apertures. Although the benefits of such systems are promising, precise synchronization and joint processing are still a challenge and the subject of much ongoing research.

1.1 State of the Art

Current research on automotive distributed radar systems includes synchronization, array design, and processing issues, with synchronization being fundamental to all of the following topics. While for the last decade frequency modulated continuous wave (FMCW) radar was the most researched type of radar, so-called digital code modulation (DCM) radars gained increased interest in recent years. Instead of using a frequency ramp, the complete bandwidth is sampled and digital modulation schemes, such as orthogonal frequency division multiplexing (OFDM), are used [13, 14, 15]. This also aims at 6G applications where integrated sensing and communication (ISAC) techniques are investigated [14, 16, 17].

Various techniques can achieve synchronization, allowing for different degrees of synchronicity as described in [18, 19, 20]. Apart from using a high-frequency coupled network, which is complicated to build and also costly, achieving near coherent features as in monostatic radars, techniques using a known target, reference paths, or identical virtual antennas are necessary, as shown in [13, 15, 20, 21, 22]. This applies to both FMCW and DCM radars. Another investigated approach is systems distributing the high-frequency signal with optical fiber networks, allowing for coherent operation [23, 24, 25]. In [19], a special hardware architecture achieves coherent features with separate signal synthesis.

Having a near coherent network, the array design and thereby the position of the nodes and antennas is also a field for research. Next to uniform arrays, distributed radar networks typically aim for a sparse array approach to achieve a good array performance with a low number of antennas. While minimum redundancy array (MRA) are a known class of sparse arrays [26], these are difficult to calculate for a high number of antennas [27]. Random optimization approaches as presented in [28, 29, 30] are typically used since computational power is available and millions of positions can be examined quickly.

Large arrays show another problem due to the far-field condition, which is typically not met anymore. Thus, range-angle correlation effects have to be expected and mitigated. The resulting phase offsets can be estimated and corrected as shown in [31, 32].

The sparse array design also paves the way for more advanced angle determination algorithms. In particular, compressed sensing methods are well-suited for sparse arrays with moderate sidelobes that normally prevent standard array processing. Different algorithms and aspects are investigated in [33, 34, 35].

1.2 Goals and Content of this Work

While most work focuses on azimuth angle determination, different aspects of distributed radar systems with elevation resolution are presented, including widely separated radar nodes and possible side effects of such setups. Since this kind of system falls into a non-coherent class of radar networks, the following chapter treats synchronization based on direct paths between the radar nodes. Different approaches are analyzed in terms of feasibility and performance. This is followed by various topics concerning array design and processing.

In Chapter 2, fundamental topics of radar systems are treated. This includes general electromagnetic field subjects and radar-related issues. A special notice is given to FMCW radars and distributed radar networks. Additionally, an overview of signal processing of radars and antenna arrays is given.

Chapter 3 gives insights into distributed radar systems for elevation resolution with widely separated radar nodes in an automotive scenario. Measurements on a simplified setup demonstrate improved elevation resolution capabilities in a short-range scenario with trilateration. However, improvement for long-range scenarios is not possible, and this demonstration shows the starting point for more sophisticated radar systems. Afterwards, aspects regarding the positioning of the nodes are investigated since a large distance between the nodes is necessary, which can only be achieved by mounting the radar on or close to the car's roof. A geometrical and simulative analysis of this situation is given, followed by measurements on a real car to confirm the findings and evaluate effects not considered.

Since non-coherent networks are limited to the trilateration or triangulation of the different radar measurements, Chapter 4 treats the synchronization of multiple radar nodes. Based on direct paths between the nodes, which are achieved by a novel designed 3D-printed antenna geometry, three different approaches for synchronization are investigated. A novel synchronization approach is presented, which can compensate for the uncorrelated phase noise of the various nodes. After an analytical examination, extensive simulations show which effects are to be expected and whether the various synchronization methods can correct them. Measurements with two and three radar nodes show the feasibility and performance of the approaches in different scenarios. The phase coherence of the entire antenna array and possible baseline offsets between the nodes are especially treated since this is often neglected or not considered by other works.

Afterwards, various aspects concerning distributed radar systems are covered in Chapter 5. In the first section, the positioning of the radar nodes and the resulting array are scrutinized under different assumptions. An analysis and compensation of near-field effects follows this. Special attention is given to the question of when and what kind of compensation is necessary in an automotive context. Subsequently, different direction of arrival (DOA) algorithms are compared, including the standard beamformer (BF), subspace-based methods as multiple signal classification (MUSIC) and compressed sensing (CS) approaches. These are applied to simulated and measured scenarios. Finally, insights are given on radar cross section (RCS) in distributed radar networks.

This is concluded by a summary of all findings and results that were achieved in this work in Chapter 6.

2 Fundamentals

This chapter provides an overview of all the fundamental principles relevant to this work. The scope and detail of the specific topic are selected according to their importance for the later chapters. In the following, a short introduction on electromagnetic waves is given in Section 2.1, including the field regions of an antenna and the scattering behaviour of electromagnetic waves. This is followed by a comprehensive overview of radar-related topics in Section 2.2 with special focus on FMCW radars and distributed radar systems. The last Section 2.3 will show the radar modules used in this work for measurements.

2.1 Electromagnetic Waves

Electromagnetic waves are the basis of all modern communication and, therefore, one of humanity's most important discoveries. While the description by the Maxwell equation is crucial for full wave simulations, many application fields use simplified models, such as the plane wave, since the full calculation of the fields in a large domain is cumbersome. Therefore, some of the basic principles are given below.

2.1.1 Field Regions and Plane Waves

Waves emitted by antennas are spherical waves, meaning the fields propagate in all directions and the wave front is a sphere [36, 37]. The surrounding area of an antenna is often categorized into three regions: reactive near-field, radiating near-field, and far-field [36]. In the very close vicinity of the antenna, reactive fields are dominating, where, for example, coupling effects can occur. The boundary for this region is approximately

$$R < 0.62\sqrt{{D_\mathrm{A}}^3/\lambda}, \tag{2.1}$$

where D_A is the largest dimension of the antenna. For tiny antennas, the boundary is

$$R < \lambda/2\pi. \tag{2.2}$$

The following region, the radiating near-field or Fresnel region, is characterized by radiating fields that are range and angle-dependent due to the spherical propagation of