



This work contributes to waveform and system design, and signal processing algorithms for automotive integrated sensing and communications (ISAC), aiming to accelerate its application at the age of 6G. This section provides an overview of relevant research developments and the motivation for the study, followed by an outline of the research methodology and the structure of this dissertation.

1.1 Motivation

1.1.1 Global Research Status of 6G

Over the past decades, the evolution of mobile communications from 2G to 5G has fundamentally reshaped the form of information exchange and accelerated global digitalization. Building upon the previous technologies, the 5G mobile networks provide three main paradigms: (i) enhanced mobile broadband (eMBB), which enables gigabit-level throughput and multimedia services, (ii) ultra-reliable low-latency communication (URLLC), which targets 1 ms latency and allows mission-critical applications, and (iii) massive machine type communications (mMTC), ensuring large scale and high density internet of things (IoT) services [1], [2]. Despite the pioneering functionalities of 5G, emerging applications put forward new requirements beyond its upper limits. Use cases such as multi-sensory extended reality (XR), connected robotics and autonomous systems, intelligent transportation systems, and personalized user experiences require not only high throughput and low latency, but also sensing capabilities and the integration of artificial intelligence (AI) [3], [4]. These requirements highlight the need for the next generation of wireless communications, i.e., the 6G.

Research on 6G wireless networks is developing rapidly around the world. In Asia, China's IMT-2030 6G Promotion Group aims to coordinate national research and development efforts in mobile communication technology and carry out international exchanges and cooperation [5], while Japan's NICT [6] and South Korea's 6GForum [7] also established 6G research projects. In North America, the USA's Next G Alliance [8] and NSF RINGS are coordinating industry and academic efforts to advance 6G research. In Europe, the flagship projects Hexa-X and Hexa-X-II [9] contribute to designing a system blueprint aiming at the sustainable, inclusive, and trustworthy 6G networks. In parallel, Germany has launched several 6G research projects. The 6G-Platform [10] provides a national strategic framework, while other projects such as 6G-ANNA [11], 6G-Campus [12], and Open6GHub [13] provide different research perspectives. Specifically, projects like KOMSENS-6G [14] and 6G-ICAS4Mobility [15] are devoted to realizing sensing



functionality in future wireless communication networks, highlighting Germany's contribution to one of the key technologies at the age of 6G.

6G mobile networks are expected to provide perception-relevant services, including but not limited to intelligent transportation, smart factory and home, environment sensing, etc., highlighting the importance of integrating sensing capability [16], [17]. However, this may lead to harsh channel conditions due to interference, while the separated sensing and communication systems significantly increase the hardware and energy costs [18], [19]. To overcome these problems, the idea of integrating the communication and sensing functions into one system is widely discussed in recent years, known as integrated sensing and communications (ISAC) [20], joint radar and communications (JRC) [21], or dual-function radar-communication (DFRC) [22]. ISAC allows communications and radar sensing systems to share the same platform and signal processing frameworks, thus reducing hardware cost and energy consumption, and improving spectrum efficiency [23], [24]. Therefore, ISAC is regarded as a key enabling technology for 6G wireless networks [25].

1.1.2 Integrated Sensing and Communications in Transportation Systems

The idea of ISAC is to integrate the communication and radar sensing into one system by allowing radar waveforms to carry data symbols, ensuring the radar receiver to extract information from the communication signals, or designing a system jointly with a flexible trade-off between communication and radar sensing, corresponding to three categories [26]:

- **Radar-centric design:** The communication function is integrated into the radar systems. Since the radar configuration is generally unaffected, the communication capabilities, like throughput, are inevitably limited by the radar signal form.
- **Communication-centric design:** Opposite to radar-centric design, the sensing function is integrated and added as a service of communication systems. The impact of adding sensing function on communication performance is slight. However, the sensing capability may be limited by the system framework.
- **Joint design and optimization:** The communication and sensing systems are designed jointly with a flexible trade-off between these two functions. Neither the communication function nor the sensing function is significantly limited; both are seen as the main service to be optimized.

One of the major use cases of ISAC is in transportation systems, where the 6G infrastructures such as roadside units (RSUs) are expected to provide services of real-time road condition monitoring, congestion management, high-resolution localization and tracking, unmanned aerial vehicles (UAV) detection, etc., thereby improving road safety and transport efficiency [27]. In addition to the infrastructure-based applications, ISAC further extends its use cases into vehicular systems. While automotive radar enables the vehicles to be aware of their surroundings, providing an improved safety and driving experience, the vehicle-to-everything (V2X) communications allow information sharing among vehicles and between vehicles and infrastructures, offering the potential for cooperative awareness and efficient coordination of traffic flows. The integration of them not only mitigates their limitations but also unlocks new synergies that are necessary for intelligent transportation systems (ITSs) [28].

In recent years, the millimeter-wave (mmWave) band (30 GHz - 300 GHz), especially the 77 GHz band [29]–[32], has become the focus of research on vehicular ISAC systems due to the small antenna size and wide bandwidth, resulting in high achievable throughput and sensing resolution [33]–[35]. While the 76-77 GHz band is assigned for the long-range applications, the short-range and mid-range ISAC systems primarily occupy the 77-81 GHz band [29], [36].

1.1.3 Open Research Problems and Focus of This Work

The application of ISAC in automotive information systems puts forward requirements for new waveform design, which is expected to provide satisfactory performance in both communication and sensing services and be able to provide reliable services in complex environments. Meanwhile, MIMO and beamforming techniques in ISAC systems have become a popular research topic since they serve as essential enablers for spatial diversity and high-resolution sensing. Moreover, advanced signal processing algorithms are desired to improve sensing accuracy and mitigate the performance loss due to the shortcomings of the waveforms. These research problems are analyzed as follows:

- **Waveform design:** The communication and sensing services are expected to be provided by a single signal and waveform. Conventional radar-centric waveforms, such as frequency-modulated continuous waveform (FMCW) and phase-modulated continuous waveform (PMCW), benefit from attractive sensing performance while suffering from poor communication capability; on the contrary, orthogonal frequency-division multiplexing (OFDM) can achieve a high data rate and is widely utilized in 4G and 5G mobile communications, but its sensing functionality is limited by the multi-carrier signal structure [37]–[39]. Therefore, it is indispensable to design or optimize a waveform and the corresponding system that can simultaneously satisfy the requirements of both functionalities.
- **MIMO and beamforming:** ISAC systems will inherently adopt multiple-input multiple-output (MIMO) and beamforming technologies since on the one hand, they enable multi-stream transmission and increase communication channel capacity; on the other hand, the MIMO radar allows the application of the virtual array technology, significantly improving sensing resolution [40]. For vehicular ISAC systems, further requirements for time efficiency and low complexity are highlighted due to the rapidly changing environments.
- **Sensing parameter estimation:** The integration of sensing functionality introduces new demands for signal processing and estimation. Most studies focus on improving the performance in detection, position/velocity estimation, tracking, imaging, and recognition [16], [41], whereas the complexity and efficiency should be considered, particularly for traffic applications due to the necessity of information freshness [42].

Motivated by these considerations, this work contributes to solving the above-listed research problems, aiming to design a waveform that performs well in both communication and sensing functions, and provide a corresponding system architecture as well as signal processing algorithm to improve sensing performance. The next section provides a brief review of relevant studies in these fields. Afterward, the objectives, contributions, and structure of this dissertation are described.



1.2 State of the Art

1.2.1 Waveform Design

Compared to traditional pulse-modulated radar, continuous waveform (CW) radar attracts more attention due to the higher energy efficiency, less space occupation, and better compatibility with communication functions [43]. Potential candidate waveforms mainly include FMCW, PMCW, OFDM, and orthogonal time frequency space (OTFS). Each waveform has their own advantages and use cases, while automotive ISAC places specific emphasis on energy efficiency, interference robustness, and timeliness [42], [44].

- **FMCW:** Most modern automotive radar systems are based on FMCW due to its low hardware complexity and favorable power efficiency [36]. Relevant research mainly focuses on its radar performance enhancement and applicability in various scenarios instead of its application in communications [45]–[48]. For instance, the performance of FMCW radar in indoor scenarios is evaluated in [45], while the impact of radio frequency (RF) hardware characteristics on FMCW radar is studied in [46]. In [47], a phase-coded FMCW radar is proposed, which efficiently suppresses the sidelobe level while maintaining the accuracy and Doppler tolerance. Interference suppression methods for FMCW radar are reviewed and discussed in [48], where a dual-recursive-least-squares algorithm is also proposed and compared with the existing methods. However, despite its favorable sensing functionality and wide application in automotive radar systems, the undesired low achievable data rate limits the applicability of FMCW in ISAC systems [39]. To the best of the author's knowledge, no research has yet addressed this problem.
- **OFDM:** In contrast to FMCW, OFDM enables an extremely high data rate transmission and reliable behavior in multipath fading channels. Consequently, it is widely applied at the age of 4G and 5G and is expected to be the dominant waveform for 6G mobile networks [49]. The application and improvement of OFDM radar have been widely discussed in recent years, and various signal processing algorithms enhancing its behavior have been developed. The studies in [50] and [51] address the challenge of the high sampling rate of the analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) at the cost of the maximum unambiguous velocity and range, respectively. The constellation design is discussed in [52], where the radar periodic autocorrelation function is improved with a trade-off of communication information entropy. Nevertheless, as a communication-centric waveform, the OFDM sensing performance inevitably suffers from the negative impact of its signal characteristics. For instance, the inherently high peak-to-average power ratio (PAPR) of OFDM signals limits transmit power efficiency and may lead to nonlinear distortions, thereby degrading radar performance. Methods such as [52]–[54] can reduce the PAPR, but still cannot achieve the low level of FMCW and PMCW. In addition, the inter-carrier interference (ICI) and inter-symbol interference (ISI) further limit the maximum tolerable velocity and range. The problems of ICI (Doppler intolerance) and ISI are respectively addressed in [55]–[63] and [64], with the compromise of either increased system complexity or reduced communication capability.
- **OTFS:** OTFS is a novel waveform and has attracted considerable attention in recent years for high-mobility ISAC applications. Unlike OFDM, which operates in the time-frequency domain, OTFS maps information symbols to the delay-Doppler domain, enabling a more

compact and sparse representation of doubly selective channels [65]. Therefore, OTFS exhibits strong robustness against dynamic environments, making it particularly suitable for high-mobility target detection. In recent years, the application of OTFS in ISAC has been actively researched. For instance, the performance and reliability of OTFS in multi-vehicle detection are investigated in [66]. The cooperation between the MIMO OTFS system and hybrid beamforming is implemented in [67], where the performance in multi-target scanning and detection is also evaluated. However, despite its advantages in high-mobility target processing and reliability in dynamic environments, OTFS also faces some practical challenges. On the one hand, OTFS generally relies on two-dimensional transforms like symplectic FFT (SFFT) and inverse symplectic FFT (ISFFT), resulting in higher complexity than OFDM [68], exacerbating the difficulty of real-time calculation. On the other hand, OTFS also suffers from ICI and ISI, requiring additional mitigation algorithms [69], [70]. In addition, although the PAPR of OTFS is lower than OFDM [71], it is still higher than FMCW and PMCW.

- **PMCW:** In contrast to OFDM and OTFS, PMCW has inherently superior radar performance. While the direct sequence spread spectrum (DSSS) with pseudo-random noise sequences (PRNs) fixes the PAPR at 0 dB and solves the problem of interference fundamentally, the single-carrier signal structure and the repetition of the transmitted symbol avoid the ICI and ISI. Consequently, PMCW has become an attractive candidate for the future vehicular ISAC systems [72]. Recent studies mainly contribute to improving PMCW radar performance. The researchers in [73] designed a PMCW-based monostatic radar system and verified its performance, while the bi-static radar is studied in [74]. Studies in [75], [76] compare the performance of different PRNs with respect to the peak-to-sidelobe ratio (PSLR) on the range-Doppler map (RDM). Addressing the problem of Doppler intolerance, [77] introduces a normalized parameter that can predict the loss in radar processing gain due to the Doppler effect, while [78] provides an all-cell Doppler correction-based solution to mitigate its influence. The work in [79] presents a reconfigurable PMCW system extending the maximum range and velocity. Considering radar signals with a large bandwidth usually experience frequency-selective fading, methods of spectrum equalization are proposed in [80]. The result shows a significantly suppressed sidelobe. However, similar to FMCW, the communication capability of PMCW is constrained by the signal structure and radar framework [39]. This drawback has not yet been sufficiently addressed in related studies.

Considering the favorable radar and anti-interference performance of PMCW and its drawbacks in carrying data, one objective of this work is to enhance its communication functionality and enable its application in realistic ISAC scenarios. This research problem is addressed in Chapter 3.

1.2.2 MIMO and Beamforming Design

Recent studies of multi-user MIMO (MU-MIMO) ISAC systems and beamforming design primarily concentrate on the separation of multiple streams and the optimization of the key performance indices using digital beamforming (DBF). However, the coexistence with virtual array, which provides extremely high spatial resolution while requiring changes in the transmitter or receiver antenna array and consequently modification in beamforming design, is missing. For instance, the study in [81] contributes to optimizing communication spectral efficiency and radar spatial spectrum matching error. The authors of [82], [83] focus on maximizing the directional gain and



suppressing the self-interference (SI) via the null-space projection (NSP) approach. The study in [84] leverages the metrics of signal-to-interference-plus-noise ratio (SINR) for communication and the Cramer-Rao lower bound (CRLB) for sensing behavior. The radar beam pattern formulation is discussed in [85], where the communication SINR is adopted as the penalty term. Physical layer security of the ISAC systems is addressed in [86], where sensing and secure communication are provided by the designed beamforming.

The coupling between the beamforming vectors of different streams generally cannot be avoided in calculations since the interference between them should be considered. The resulting iterative optimization may lead to significantly increased computational effort, which is undesired in vehicular applications due to the requirement of information freshness [42]. Addressing the issue of complexity, the concept of signal-to-leakage-plus-noise ratio (SLNR) is introduced in [87], which decouples the optimization of the SINRs by changing the interference term to the leakage to other channels. It is explained in [88] that the SLNR can approximate SINR in symmetric channels. The application of SLNR in the OFDM-ISAC system is implemented in [89], the designed DBF can guarantee a high SINR at both the communication and radar receivers while effectively suppressing the SI. Similarly, studies in [90], [91] involve signal-to-clutter-plus-noise ratio (SCNR) in beamforming design, where clutter instead of interference or leakage is taken into account. Due to the low complexity and favorable performance, SLNR-based DBF is employed in this work. Considering the fact that instantaneous channel state information (CSI) is hard to obtain in dynamic environments, the DBF based on the statistical channel covariance matrix is designed, details are described in Chapter 4.

1.2.3 Radar Range-Doppler-Angle Estimation

Radar signal processing includes the processes from signal generation to propagation, reception, parameter (range/velocity/angle) estimation, target detection and tracking, and multipoint data fusion, etc. This study concentrates on improving the parameter estimation accuracy, thus studies in target detection [92]–[96] & tracking [97]–[100] and multipoint data fusion [101]–[105] are not further discussed here, while studies in signal generation, propagation, and reception are mainly in the field of waveform/system design and beamforming.

Current radar parameter estimation approaches mainly include periodogram, multiple signal classification (MUSIC), estimation of signal parameters via rotational invariance techniques (ESPRIT), compressive sensing (CS), and correlation (PMCW-only); their fundamentals and relevant studies are briefly reviewed as follows:

- **Periodogram:** This is a classical method employing fast Fourier transform (FFT)/inverse fast Fourier transform (IFFT) for parameter estimation and has been widely used in radar systems. Periodogram is the easiest to implement and benefits from low complexity, but suffers from problems of low resolution/accuracy and high sidelobes due to the property of the sinc function in FFT/IFFT. The sidelobes can be simply suppressed by applying window functions, which also extends the width of the mainlobe. The improvement in accuracy has been studied in [62], [76], [106]–[110]. The conventional interpolation method is implemented in [106], while the methods of upsampling or zero-padding are investigated in [76], [107], [108]. Approaches of fine estimation via linear approximation can be found in [109], [110], which involve the samples in the mainlobe to calculate the accurate value, whereas the accuracy is constrained by the linear optimization process. The interpolation by optimization method is discussed in [62], where the delay and Doppler are fine-estimated

via a least square (LS) optimization problem. The optimization method can significantly improve sensing accuracy and suppress the sidelobes with a high computational cost, since the RDM estimation should be implemented repeatedly to obtain an accurate result. Overall, methods attaining extremely high accuracy with low computational effort are still missing.

- **MUSIC:** The radar parameters estimation leverages the orthogonality between the signal and noise subspaces, thus it can achieve a super-resolution estimation and distinguish multiple close targets. After the eigen decomposition of the signal covariance matrix, MUSIC constructs the pseudo spectrum and extracts peaks as the target, where the resolution highly depends on the spectrum search granularity. Consequently, MUSIC generally requires high computational effort, which is proportional to its resolution. Therefore, relevant works [83], [111] mainly studied its application in the angle domain, where the searching step is generally much fewer than range and Doppler estimations.
- **ESPRIT:** ESPRIT is also based on the separation of signal and noise subspaces, while the spectrum search is avoided by exploiting the rotational invariance of subarrays, thereby achieving super-resolution estimation with lower complexity than MUSIC, but the rotational invariance raises strict requirements on array structure and increases sensitivity to noise. It is analyzed in [62] that due to the disadvantage in robustness and versatility, ESPRIT is less favorable than the periodogram for radar parameter estimation in most cases.
- **CS:** Compressive sensing is a signal sampling and reconstruction theory applicable to sparse signals [112]. Compared to the periodogram, CS requires much fewer samples for estimation, and the original signal is reconstructed by solving the optimization problem. Therefore, CS can achieve super-resolution estimation in sparse scenarios with much less burden on ADC and memory [113]. A disadvantage is that the complexity in optimization is high due to the large data size [114], while the off-grid effect may impact the estimation accuracy and destroy the sparsity [115]. Methods of grid densification and off-grid estimation can be found in [116]–[118], which nevertheless further increase the complexity. Another shortcoming compared to the periodogram is the sensitivity to noise, whereas the periodogram suppresses it in the processes of FFT and IFFT.
- **Correlation:** PMCW radar receiver calculates the range information utilizing the correlation property of the PRNss, providing favorable anti-interference performance, which is an advantage compared to other waveforms. However, compared to FFT or IFFT-based estimation, correlation in the fast time domain is computationally inefficient and cannot support expansion modules such as windowing or accuracy improvement methods. The idea of replacing the correlation by element-wise multiplication in the frequency domain is discussed in [39], where the range profile is obtained by performing an IFFT on the multiplied spectrum. This modification overcomes the drawbacks of correlation while maintaining its favorable anti-interference property.

In summary, it is essential to design an algorithm with high accuracy, efficiency, robustness, and practicality. This work provides a solution for this research problem, details are described in Chapter 5.



1.3 Contributions and Structure

The advantage of applying ISAC in traffic scenarios is significant, whereas the discussed research problems have to be solved. This work first addresses the issue in waveform design, then provides a high-performance and low-complexity beamforming design and a radar denoising and fine estimation algorithm. The contributions are listed in the following:

- Waveform design [119], [120]: This work chooses PMCW as the basic waveform due to its superior performance in radar sensing and interference suppression. Addressing its drawbacks in communication capability, a code-orthogonal PMCW (CO-PMCW) transmission scheme is proposed, which solves the problem by simultaneously transmitting radar (pilot) and communication (data) sequences. The separation of data from the radar signal enables a flexible communication system configuration and thus allowing a high data rate. Meanwhile, the communication receiver can always track the CSI using the continuously transmitted pilot, improving the performance in dynamic channels. The simulation results show that CO-PMCW can achieve a significantly higher throughput than PMCW, while the mutual interference (MI) between the radar and communication signals leads to slightly increased noise on the radar RDM.
- MIMO system design and beamforming [121], [122]: CO-PMCW suffers from MI between the radar and communication sequences, and the implemented single-input single-output (SISO) system framework cannot perform angle estimation. To this end, the CO-PMCW SISO system is extended to a MU-MIMO system, named code-space-orthogonal PMCW (CSO-PMCW), where the added spatial orthogonality between the radar and communication streams is achieved by the DBF. The transmitter employs SLNR to approximate the maximization of SINR. The communication and radar receivers maximize the SINR by the minimum variance distortionless response (MVDR) approach. Besides, the combination of DBF and virtual array technology is discussed. The simulation results show that the radar dynamic range of CSO-PMCW with the designed DBF approaches that of conventional PMCW.
- Radar denoising and fine estimation (DFE) algorithm [122], [123]: The aim is to provide a cleaner RDM for target detection and a high accuracy estimation with low complexity. The algorithm is based on periodogram and leverages the mathematical formula of the RDM and angle profile. Since the contributions of the reflected signals are equivalent to the windowed response with different amplitudes and shifts in the range and velocity domains, the fine estimation can be implemented by minimizing the difference between the modeled RDM/angle profile and the estimated ones. The signal is then reconstructed using the estimated parameters and canceled from the received one, thereby removing the contributions of the detected targets and revealing weaker reflections previously masked by them. The designed algorithm can cooperate with various waveforms. Its applications in CSO-PMCW and OFDM radar receivers are implemented in [122] and [123], respectively. The simulation results show that the algorithm can significantly improve the radar dynamic range and sensing accuracy with much lower computational effort than other approaches. Moreover, it is demonstrated that the DFE algorithm is capable of multi-target processing and does not affect the communication functionality.
- Overall system design and use case analysis [122]: The CSO-PMCW MU-MIMO ISAC

system is built on MATLAB, where all the designed modules including the DBF and DFE algorithm are integrated. The system performance is simulated in a real-world-based environment constructed on Winprop, a 3D ray-tracing channel simulation tool provided by Altair, where the channel model of the 'Leipziger Platz' in Berlin, Germany, is simulated. The applicability of the designed system in realistic scenarios is analyzed.

The corresponding published papers are listed as follows:

- **Y. Su**, V. Shatov, M. Lübke and N. Franchi, "Improving Resource Efficiency of PMCW-Based JCRS Systems: Simultaneous Transmission of Pilot and Data via Orthogonal Codes," 2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Toronto, ON, Canada, 2023, pp. 1-7, doi: 10.1109/PIMRC56721.2023.10293888. [119]
- **Y. Su**, V. Shatov, N. Franchi and M. Lübke, "A Code-Orthogonal PMCW Transmission Scheme for Improving Communications Performance in JCAS Systems," in IEEE Access, vol. 12, pp. 29673-29689, 2024, doi: 10.1109/ACCESS.2024.3369415. [120]
- **Y. Su**, N. Franchi and M. Lübke, "Code-Orthogonal PMCW MIMO ISAC System: Digital Beamforming for Pilot and Data Separation," 2025 28th International Workshop on Smart Antennas (WSA), Erlangen, Germany, 2025, pp. 274-278, doi: 10.1109/WSA65299.2025.11202849. [121]
- **Y. Su**, N. Franchi and M. Lübke, "A Low-Complexity Denoising and Fine Estimation Algorithm for MIMO Radar," in IEEE Transactions on Radar Systems, vol. 4, pp. 690-696, 2026, doi: 10.1109/TRS.2026.3677521. [122]
- **Y. Su**, G. Zhang, N. Franchi and M. Lübke, "ISAC-Enabled OFDM Radar: ICI and Off-Grid Effect Suppression via Signal Reconstruction," in IEEE Transactions on Vehicular Technology, vol. 75, no. 2, pp. 2101-2116, Feb. 2026, doi: 10.1109/TVT.2025.3606218. [123]

Besides the above-mentioned aspects, the author also contributed to the study of coordinated multipoint (CoMP) ISAC in 6G mobile networks [124], where the network architecture, operation modes, clustering schemes, and key technologies are analyzed. The simulation demonstrates its favorable performance in mobile networks and explains the advantages and disadvantages of different operation modes.

- **Y. Su**, M. Lübke and N. Franchi, "Coordinated Multipoint JCAS in 6G Mobile Networks," in IEEE Access, vol. 12, pp. 98530-98545, 2024, doi: 10.1109/ACCESS.2024.3428831. [124]

In addition, the author has participated as a co-author in publications [125]–[132]. The work in [125] introduces a code-division multiple access (CDMA)-based vehicle-to-vehicle (V2V) communication system model, where the joint phase-frequency compensation approach guarantees reliable communication performance in dynamic channels. The impact of RF hardware characteristics on PMCW-based 77 GHz ISAC system is evaluated in [126], where the result shows that the non-linearity of the transmitter power amplifier (PA) and noise figure of the receiver low noise amplifier (LNA) have the dominant impact. The cooperative radio sensing for spatial electromagnetic analysis is discussed in [127], where the existence form of spectrum sensing



in future wireless networks is analyzed. An AI-based transmitter localization and waveform classification method is studied in [128], being achieved by a long short-term memory (LSTM)-deep neural network (DNN). Additionally, the author led the work package 8.1 of the project 'Open6GHub', cooperating with the partners to develop an overall concept of resilience-by-design (RBD) and security-by-design (SBD) on the basis of the defined requirements and necessary system properties. As a result, a joint paper [129] is worked out, which summarizes the initial studies of Open6GHub in relevant technologies and describes the concept of RBD from different perspectives. Additionally, the use cases and unsolved challenges are analyzed. Supervised learning for wireless signal classification is studied in [130]. The study in [131] proposes a scalable MIMO framework with partially connected hybrid beamforming for ISAC systems, where a fairness power distribution of the communication and radar receivers is achieved by an interior-point method. Further, the author participated in the analysis of emerging PHY technologies for 6G in the project '6G-ANNA' and the writing process of the resulting positioning paper [132]. The corresponding peer-reviewed papers are listed here:

- M. Lübke, **Y. Su** et al., "Full Physical Layer Simulation Tool to Design Future 77 GHz JCRS-Applications," in IEEE Access, vol. 10, pp. 47437-47460, 2022, doi: 10.1109/ACCESS.2022.3170919. [125]
- M. Lübke, **Y. Su** and N. Franchi, "Evaluating RF Hardware Characteristics for Automotive JCRS Systems Based on PMCW-CDMA at 77GHz," in IEEE Access, vol. 11, pp. 28565-28584, 2023, doi: 10.1109/ACCESS.2023.3259725. [126]
- V. Shatov, M. Lübke, **Y. Su** and N. Franchi, "On Integrated Cooperative Radio Sensing for Spatial Electromagnetic Analysis in 6G," 2023 IEEE Future Networks World Forum (FNWF), Baltimore, MD, USA, 2023, pp. 1-8, doi: 10.1109/FNWF58287.2023.10520344. [127]
- V. Shatov, N. Shanin, B. Perner, **Y. Su**, N. Franchi and M. Lübke, "LSTM-DNN-Based Joint Wireless Signal Waveform Classification and Blind Transmitter Localization," 2024 19th International Symposium on Wireless Communication Systems (ISWCS), Rio de Janeiro, Brazil, 2024, pp. 1-6, doi: 10.1109/ISWCS61526.2024.10639099. [128]
- L. Khaloopour, **Y. Su** et al., "Resilience-by-Design in 6G Networks: Literature Review and Novel Enabling Concepts," in IEEE Access, vol. 12, pp. 155666-155695, 2024, doi: 10.1109/ACCESS.2024.3480275. [129]
- V. Shatov, **Y. Su** et al., "Supervised Learning of Wireless Signal Waveforms in the Era of Radar-Communications Convergence," Proceedings of the 16th IFIP Wireless and Mobile Networking Conference (WMNC), Leuven 2025. [130]
- M. Zhang, **Y. Su**, N. Franchi, R. Weigel and T. Reissland, "Hybrid Beamforming for Multi-User Joint Communication and Sensing With URA Under Partially Connected Architectures," in IEEE Access, vol. 13, pp. 170395-170409, 2025, doi: 10.1109/ACCESS.2025.3615453. [131]
- B. Banerjee et al., "6G PHY: Insights From 6G-ANNA Research Initiative," in IEEE Open Journal of the Communications Society, doi: 10.1109/OJCOMS.2026.3658132. [132]

This dissertation includes the contributions of [119]–[123] and is organized as follows: