Polarimetric MIMO arrays for automotive radar

Preliminary literature review report

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Abstract

The goal of this document is to present a preliminary literature review report, summarizing roughly the first months of research and consisting of an initial dive into the state of the art in the area of polarimetric MIMO radar for automotive applications in search for deep insights and directions of further advancements.

Chapter 1

Introduction

Automotive radar is a rapidly-evolving field of research, driven by the increasing demand for enhanced driver safety and the eventual realization of autonomous vehicles [1]. While the initial vision of fully autonomous driving has faced regulatory and technological hurdles, the major focus of the industry has pragmatically shifted. The immediate goal is now the improvement of driver safety through advanced driver-assistance systems (ADAS). This forms a crucial foundational step, with the progressive automation of further features over time being the pathway towards full vehicle autonomy.

Modern ADAS increasingly rely on robust environmental perception to ensure safety and reliable operation across a wide range of road conditions. Among all sensing modalities, millimetre-wave radar at 77–81 GHz remains uniquely resilient to adverse weather, low visibility, and non-cooperative targets. While contemporary automotive radars provide accurate range, velocity and angular estimates, their classification capability remains fundamentally limited. Radar systems in vehicles are predominantly single-polarized MIMO arrays, optimized for geometric detection but not for detailed scattering characterization. As a result, the ability to distinguish vulnerable road users (VRUs) – including pedestrians, cyclists, and scooter riders – from background clutter or other vehicles is still insufficient for high-level scene understanding [2].

In contrast, radar polarimetry has long demonstrated powerful discrimination capabilities in other domains such as remote sensing, weather radar, and synthetic aperture radar (SAR). Polarimetric measurements capture how objects transform the polarization state of the incident electromagnetic field, thereby revealing structural, material and orientation-dependent scattering properties. These additional degrees of freedom can support classification tasks that are fundamentally unattainable with intensity-only radar data. Yet, despite its maturity in other fields, polarimetry has not been adopted in commercial automotive radar. Early research prototypes indicate its potential, but the fundamental theoretical, technological and calibration challenges remain unresolved.

Furthermore, the transition to high-resolution 2D MIMO arrays in automotive radars introduces new opportunities for capturing polarization-diverse scattering. Larger virtual apertures, wide angular fields of view and sparse array concepts can benefit polarimetric imaging – but they also exacerbate issues such as cross-polar coupling, mutual coupling between antennas, phase-centre misalignment and channel imbalance. These limitations motivate a systematic reassessment of array topologies, antenna technologies, and processing schemes required for polarimetric MIMO radar at W-band.

This literature review therefore aims to synthesize the state of the art in:

- radar polarimetry theory and its applicability to automotive environments,

- antenna technologies suitable for dual-polarization operation at 77–81 GHz,
- MIMO array topologies and multiplexing schemes relevant for polarimetric systems, and
- signal-processing and calibration methods required for polarimetric reconstruction.

The synthesis identifies critical gaps in current knowledge – most notably the lack of a polarimetric method suitable for dynamic road scenes, Doppler-resolved polarimetry at mmWave, and MIMO array designs optimized jointly for polarization purity and automotive integration. These insights form the basis for the research contributions of this PhD: the development of a new polarimetric method for automotive radar, the design of a polarimetric MIMO array demonstrator, and the establishment of a dedicated measurement experiment for extracting target polarimetric signatures.

Chapter 2

Radar polarimetry

Although the foundational ideas of radar polarimetry date back to the 1970s and can be considered a mature concept, with the 1980s and 1990s representing a golden period of theoretical and experimental development, [3] its application potential in the automotive industry began to emerge only in the previous decade. Consequently, the field of polarimetric automotive radar is still very much in its infancy; nonetheless, it holds a compelling promise for achieving higher reliability and sophistication in sensors for ADAS and autonomous driving. This promise has already captured the attention of major automotive companies and research institutes, prompting them to provide viability confirmations [2]. A handful of publications has pioneered the proof of concept through complete system implementations [4]. Furthermore, the rapidly increasing interest and innovation in this area are evidenced by the recent emergence of longer monographs focusing specifically on the topics and advancements of polarimetric radar for automotive applications [5].

2.1 Electromagnetic polarization fundamentals

Electromagnetic waves can be decomposed into orthogonal linear, circular or elliptical polarization states, each associated with a specific temporal evolution of the electric field vector. In radar applications, polarization serves as an additional dimension for characterizing scattering mechanisms: targets may preserve, transform or depolarize the incident wave depending on their geometry, surface material, roughness and orientation. These transformations provide valuable classification features that are absent in scalar radar measurements [3].

The description of polarization typically relies on the Jones vector for coherent fields and the Stokes vector or coherency matrix for partially coherent and incoherent fields. At automotive millimetre-wave frequencies, high coherence of FMCW radars allows Jones and coherency representations to remain applicable. The polarization purity of the transmitted and received waves, however, is strongly influenced by antenna cross-polarization discrimination (XPD), PCB anisotropies, and mutual coupling – highlighting the need for careful array design.

2.2 The scattering matrix and polarimetric models

The basic mathematical representation of polarimetric radar interaction is the 2×2 Sinclair scattering matrix

$$\boldsymbol{S} = \begin{pmatrix} S_{\mathrm{HH}} & S_{\mathrm{HV}} \\ S_{\mathrm{VH}} & S_{\mathrm{VV}} \end{pmatrix}, \tag{2.1}$$

where the indices denote the transmit and receive polarization. This matrix captures the target's ability to preserve or convert polarization states. Under the monostatic assumption, reciprocity often implies $S_{\mathrm{HV}} = S_{\mathrm{VH}}$, though this is not always valid in near-field or rapidly varying scenarios typical for automotive radar.

Add sources...

Depending on the target category, different scattering behaviours dominate:

- Smooth metallic surfaces: dominant co-polarization terms, low depolarization.
- Pedestrians/cyclists: complex polarimetric signatures due to limbs, moving parts, and heterogeneous materials.
- Road infrastructure: specular reflections with limited cross-polarization except under oblique incidence.

These behaviours motivate polarimetry for VRU classification, but also complicate measurement interpretation at short ranges.

2.3 Polarimetric decomposition techniques

A variety of decomposition methods allow interpretation of the scattering matrix. Classical approaches include:

- Pauli decomposition (surface, dihedral, and helix scattering components),
- Krogager's decomposition,
- Cloude-Pottier eigenvalue/eigenvector analysis (entropy, anisotropy, alpha angle),
- Huynen parameters (geometric and physical attributes of the scatterer).

These methods were historically developed for *far-field SAR or remote sensing scenarios* with static or slowly varying targets. Automotive radar challenges these assumptions due to:

- rapidly moving targets,
- near-field or intermediate-field operation,
- FMCW sweep time constraints,
- multipath on reflective ground surfaces,
- limited number of polarization channels (often dual-polarization or hybrid-polarization).

Thus, while classical decomposition techniques provide conceptual grounding, they cannot be directly applied to automotive scenarios without new theoretical extensions.

2.4 Suitability for automotive radar

Automotive scenes differ fundamentally from the operating conditions assumed in polarimetric radar theory:

- Short range (5–60 m): transition region between near-field and far-field, invalidating plane-wave assumptions.
- High dynamics: scattering matrices evolve on millisecond timescales due to limb motion and ego-vehicle motion.
- Multipath dominance: ground reflections and vehicle surfaces introduce depolarization not predicted by classical models.
- Multiplexing constraints: sequential polarimetric switching increases Doppler ambiguity when combined with TDM-MIMO.

These discrepancies justify the development of *new polarimetric methods*, potentially including Doppler-resolved polarimetric processing and joint spatial-polarimetric feature extraction.

Notes

- Why polarimetric radar?
  - Weishaupt et al. [6]: “In automotive applications, the additional information on the scattering process derived from polarimetry can be used for an improved classification of other road users [1], [2] or the enhanced perception of the static environment for localization purposes [3]. A typical new result through applying polarimetry is an estimate of whether an even or odd number of reflections occurred at a scatterer. This allows drawing conclusions on the object’s geometries.”
  - ...
- Major challenges [7]:
  - Increment of the cross-polarization level of the radiation pattern in off-broadside measurement
  - Varying antenna phase centres in MIMO polarimetric radar
  - Complexity of polarimetric radar calibration
  - Lack of comprehensive system model for joint development of antennas and calibration strategies

[orange]Notes

Chapter 3

Antenna types for polarimetric MIMO automotive radar

Automotive radar systems operating in the 77–81 GHz band demand compact, highly integrated antennas that offer robust dual-polarization capabilities for polarimetric sensing. Achieving high cross-polarization discrimination (XPD), wide field-of-view (FoV), and manufacturability within stringent size and cost constraints presents significant design challenges. The radar antennas must balance beam shaping, mutual coupling suppression, and thermal/mechanical stability to enable accurate object classification in advanced driver assistance systems (ADAS). This review critically evaluates existing antenna technologies recognized for their suitability and limitations in this application domain.

3.1 Scope and requirements

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Automotive radar imposes several constraints on antenna performance, guiding the interpretation of the state of the art:

- *Polarization purity:* Cross-polar discrimination (XPD) of > 20 dB across $\pm 60°$ field-of-view (FoV).
- *Integration:* Compatibility with compact radar front-ends, low-profile PCB or package-level integration.
- *Mutual coupling:* Sufficient isolation between MIMO elements to enable virtual aperture synthesis.
- *Manufacturability and cost:* Feasible process for high-volume production.
- *Thermal stability:* Minimal gain/phase drift under automotive temperature cycles.

3.2 Overview of radar front-end technology

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This section introduces the principal antenna families explored in recent literature, organized by structural and electromagnetic characteristics relevant to polarimetric performance.

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Microstrip patch antennas are extensively used in commercial 77 GHz radar due to their compatibility with multilayer PCB manufacturing. Dual-polarized versions are achieved using orthogonal feeds (probe, aperture, or proximity-coupled). Their main drawbacks are limited bandwidth and sensitivity to fabrication tolerances, which directly degrade polarization purity.

Substrate integrated waveguide (SIW) and **LTCC waveguide**-based antennas exhibit low loss and excellent XPD. Their robustness against temperature-induced deformations makes them suitable for high-frequency radars. However, their increased process complexity may be undesirable for large MIMO arrays unless the design is highly modular.

Gap waveguide (GW) and **ridge gap waveguide** (RGW) technology provides low loss, high isolation, and excellent dual-polarization characteristics. It avoids the need for electrical contact between layers, which eases millimetre-wave fabrication. This class currently represents one of the most promising platforms for dual-polarized MIMO.

Slot-based antennas (cavity-backed slots, CP-slots, and slanted slot arrays) offer naturally high polarization purity and robustness. Their main challenges relate to bandwidth and integration complexity when a wide field of view is required.

Horn and horn-like antennas exhibit outstanding gain and polarization purity but are impractical for system-level automotive integration. They are most relevant as reference antennas or measurement standards.

Dielectric resonator and rod antennas (DRAs) and rod antennas offer wide bandwidth and high radiation efficiency. The main challenges remain mechanical robustness and integration in thin radar package stacks.

3.3 Comparative analysis of antenna technologies

The following table summarizes representative antenna types found in the literature and highlights key parameters that influence their suitability for polarimetric automotive MIMO arrays.

Table 3.1: Comparison of antenna types for 77–81 GHz polarimetric MIMO radar

Antenna type	**DP**	**BW**	**Loss**	**XPD**	**SLL**	**Isolation**	**Compact**	**Other considerations**
SIW-aperture-coupled microstrip patch antenna [8]–[10]	Yes	Narrow	Low	High	Moderate	Moderate	Yes	PCB-compatible, tight spacing, thermal concerns
Series-fed patch antenna array [11]	Yes	Narrow	High	Moderate	High	Moderate	Yes	Cost-effective, beam squint at wide scan
Series-parallel-fed square patches [12]	Yes	Moderate	High	High	Moderate	Moderate	Yes	TMD-MIMO, single CP or dual LP capabilities
Series-fed aperture-coupled patches [13]	Yes	Narrow	Low	Very high	Low	High	Yes	–
Series-fed vertically-loaded multi-layer patch array [14]	Yes	Wide	Moderate	High	Moderate	High	Yes	Stacked vias reduce surface wave and widen BW
Corrugated sectoral horn antenna array [4], [15]	No	Wide	Low	Very high	Very low	Very high	No	Bulky, high cost, integration challenges
Ridge gap-waveguide polarimetric antennas [16], [17]	Yes	Moderate	Low	Very high	Low	Very high	Yes	Excellent PCB integration, good FoV
Mixed edge- and aperture-fed multi-layer patch antenna [18]	Yes	Narrow	High	High	Moderate	High	Yes	Complex feeding
L-shaped horn antenna array [19]	Yes	Wide	Low	Very high	Moderate	High	No	Good PCB integration, lower gain
Cavity-backed ring-slot slot planar antenna [20]	Yes	Narrow	Moderate	Very high	Moderate	Moderate	Yes	High F/B ratio, circular polarization
Cavity-slotted waveguide antenna [21]	No	Wide	Low	Very high	Low	High	Yes	–
Dielectric rod antenna [22], [23]	Yes	Wide	Low	High	Moderate	Moderate	No	Robust design
Hybrid thin-film multi-layer antenna [24]	No	Wide	Very high	Low	High	Low	Yes	Poor efficiency (< 40%), limited beamwidth

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Antenna type	DP	BW	Loss	XPD	SLL	Isolation	Compact	Other considerations
LP comb-line microstrip stub array [25]	No	Narrow	High	Limited	Moderate	Moderate	Yes	Decent XPD only near boresight
Slotted SIW array with bent slots [26]	No	Narrow	Low	Very high	Low	High	No	Minor beam squint, LTCC
Stepped SIW quasi-pyramid horn antenna [27]	Yes	Wide	Low	Very high	Low	High	Yes	High gain, emerging design
Cavity-backed bow-tie patches [28]	Yes	Moderate	Moderate	High	Moderate	Moderate	Yes	Good FoV
Spline-shaped microstrip edge-fed antennas [29]	Yes	Narrow	Moderate	Moderate	Moderate	Moderate	Yes	Simple structure, easy fabrication

Insights. Based on the literature survey and the quantitative comparison in Table 3.1, several conclusions can be drawn for the design of a polarimetric MIMO array:

1. *Gap waveguide antennas provide the best balance of XPD, mutual coupling, and thermal stability*, making them strong candidates for dual-polarization MIMO demonstrators.

2. *Microstrip patches remain attractive for prototyping* due to ease of fabrication, but their limited polarization purity and sensitivity to tolerances make them challenging for high-fidelity polarimetry.

3. *SIW/LTCC designs offer excellent isolation* and are compatible with module-level integration, though process complexity must be managed.

4. *Slot antennas exhibit robust polarization purity*, but may require careful bandwidth enhancement for wide FoV radar.

Additional notable technology platforms

- Metasurface/metamaterial antennas: Antennas leveraging metasurfaces can offer tailored polarization control and mutual coupling reduction. This technology is promising for miniaturization and XPD enhancement though requires further experimental validation in automotive radar contexts.

- Reconfigurable antennas: Utilizing tunable materials or MEMS can enable adaptive polarization states and beam steering, potentially benefiting polarimetric MIMO performance and multifunctionality.

- Low noise and active antennas: Integration with active circuitry (LNA or phase shifters) at the antenna element level improves noise figure and overall system sensitivity but complicates design and thermal management.

- 3D-printed antennas for millimetre-wave: Emerging additive manufacturing allows complex geometries with lightweight materials, which might open new design spaces for compact, high-performance antennas suitable for radar demonstrators.

Implications. The findings guide the selection of antenna elements for the polarimetric MIMO demonstrator developed in this project. High-XPD, low-coupling technologies such as SIW and gap-waveguide antennas appear most capable of supporting robust polarimetric measurements and scalable sparse-MIMO topologies. Practical aspects such as manufacturability, integration with the transceiver front-end, and thermal robustness further influence the final choice.

Chapter 4

MIMO array topologies

Add sources...

Existing MIMO array designs for automotive radar predominantly use linear or planar sparse layouts optimized for angular resolution and cost-efficient implementation. TDM-MIMO architectures dominate current commercial systems, typically leveraging 3–4 transmitters with 4–8 receivers to synthesize virtual arrays of 12–48 channels. Recent research explores 2D MIMO arrays, co-prime and nested sparse layouts, and wide-aperture imaging arrays. However, most published designs assume a single polarization, leaving the interaction between sparsity and polarization purity largely unexplored. Only a few prototypes integrate dual-polarization at W-band, and these often suffer from phase-centre mismatches, reduced aperture efficiency and severe cross-polar coupling. As a result, no established array topology exists that simultaneously optimizes spatial resolution, polarization isolation and multiplexing feasibility for a fully polarimetric automotive radar.

4.1 MIMO fundamentals

The concept of MIMO antenna systems is a well-established and extensively published area within telecommunications, where transmitting data over multiple uncorrelated signals results in additional information about the state of the communication channel, aggregating effects like multipath propagation and other types of signal fading or delays. This information is leveraged to estimate the channel matrix which is then used to compensate for propagation effects to recover the transmitted data.

While the foundational idea of MIMO has been successfully carried over to radar technology, the problem formulation is adapted: the primary goal of radar is the precise estimation of the channel matrix, which encapsulates information about propagation effects, including time delay, Doppler shift, and angle of arrival [30], [31]. The success of this communications-to-radar transformation has inspired extensive research, leading to key advancements and further classifications, such as the division of the general array concept into colocated and distributed MIMO [32], [33]. However, this concept transfer must be undertaken with care, respecting and integrating the existing knowledge of traditional radar technology, as a direct, uncritical adaptation can lead to flawed conclusions, occurrences of which were found mainly in the case of distributed MIMO, where some contributions transpired to be either redundant re-discoveries of concepts from multistatic radar, or simply incorrect statements [34].

In the realm of automotive applications, the use of MIMO systems is inherently limited to colocated MIMO arrays due to space and geometric constraints. From a signal processing perspective, this topic is now well-studied, and the benefits the concept brings – such as increased virtual array size, improved angular resolution, and enabled adaptive processing – are wellunderstood and documented [35]. This comprehensive understanding is evident in the detailed literature, defining concepts like parameter identifiability [36] to showcase the merits of MIMO radar. The maturity of the field is further highlighted by the existence of specialized reference books dedicated entirely to the topic of MIMO radar [37].

Notes

- Double down on the distinction between colocated and distributed MIMO, highlighting that colocated configurations enable coherent transmission and detection, whereas distributed MIMO brings spacial diversity gain to the table.
- Mention papers combining the benefits of both: [38], [39] and others.
- Advantages [39]:
  - Widely-separated antennas (distributed MIMO) can help overcome target scintillation (i.e., RCS fluctuation).
  - Flexible transmit beampattern design of a colocated MIMO, based on covariance matrix optimization, can help maximize power in directions of interest while minimizing backscattered signals correlation. $\rightarrow$ Significant improvement of adaptive techniques
  - MIMO radar scheme can achieve higher resolution and improve clutter rejection capabilities.
- Why MIMO radar (TBD)
  - Concept of virtual array $\rightarrow$ larger effective array $\rightarrow$ better angular resolution
  - Diversity gains, increased SNR
  - 2D MIMO radar enables shaping the elevation pattern
- Major challenges:
  - Not enough analytical work in virtual array synthesis, especially 2D
  - EM-informed design and signal processing, such as missing links between parasitic physical phenomena like antenna element coupling and errors in processing algorithms

4.2 Sparse and 2D MIMO arrays

4.3 Polarimetric MIMO designs

Notes

- Only consider fully polarimetric radar?
- “Constructing an interleaved transmit array of single-polarized elements, e.g., even and odd-numbered elements radiating horizontal and vertical polarizations, respectively, results in different phase centres for each polarization, and hence in “polarization squint”. Dual-polarized elements completely avoid this problem but require an OMT for each element.”
- Is the hardware overhead of dual-polarized elements worth it in case the squint can be calibrated for?

Chapter 5

Polarimetric and MIMO signal processing

Polarimetric processing techniques in classical radar systems rely on scattering matrix reconstruction and decomposition methods such as Pauli, Krogager or Cloude-Pottier analysis. These methods, however, assume far-field illumination, stationary targets and ideal polarization channels – conditions that are rarely met in automotive environments. Recent work explores hybrid or sequential polarimetry for FMCW radars, but multiplexing overheads often lead to Doppler ambiguities or channel imbalance. To date, no standardized processing pipeline exists for extracting polarimetric features from dynamic automotive scenes, particularly when combined with MIMO virtual aperture reconstruction. This leaves substantial room for defining new polarimetric processing frameworks tailored to short-range, high-mobility applications.

5.1 Scattering matrix reconstruction

5.2 Polarimetric decomposition for dynamic scenes

5.3 Doppler-resolved polarimetry

Notes

- Polarimetric processing: Many papers repeating the motivation that polarization measurements provide more information dimensionality for classification of shapes, such as scattering types, etc., based on the polarimetric decomposition of choice.
- Major challenges:
  - Need to develop a polarimetric decomposition method for VRU classification.
  - More research needed on characterization of road-scenario scattering mechanisms.
- Target classification: Most people train a CNN/graph-CNN/DL/RL or any other ML model on radar point cloud data consisting of peak detections. However, it suffers from drawbacks propagated from the peak-detection algorithms like CFAR. It might (and it shows to) be more convenient to perform classifications on the 4-D radar cube/tensor data or its projections/cuts/etc.
  - Major et al. [40]: First people to perform vehicular target classification on pre-detection data.
  - Tilly et al. [41]: Object classification and detection on pre-CFAR data.

Chapter 6

Calibration methods

Calibration of polarimetric radar systems is essential due to inevitable amplitude/phase imbalance, mutual coupling and cross-polar leakage. While well-established calibration routines exist for SAR and weather radar, few automotive-compatible solutions have been documented. The combination of TDM-MIMO sequencing, dual-polarized antennas and PCB-based front-end electronics creates significant channel non-idealities that classical methods do not address. The recent introduction of compact polarimetric reflectors and near-field calibration targets offers a starting point, but a consistent calibration methodology for 77–81 GHz polarimetric MIMO arrays remains an open research topic.

6.1 MIMO calibration

6.2 Polarimetric calibration

6.3 Automotive constraints

Notes

- Not the main focus of my research – mention potential sources
- Traditional array calibration: Vasanelli, Buitrago, and Harter (unread)
- Polarimetric: Changxu, Visentin, and Weishaupt

Chapter 7

Synthesis of open challenges

7.1 Scientific gaps

7.2 Technological gaps

7.3 Experimental gaps

Chapter 8

Summary and outlook

TBD

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