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.

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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

Chapter 3

Antenna types for polarimetric MIMO automotive radar

The antenna element serves as the fundamental physical interface of the radar sensor, defining the initial boundary conditions for signal fidelity. In the context of polarimetric MIMO automotive radar operating in the 77 GHz to 81 GHz band, the antenna design is governed by a stringent conflict between electromagnetic purity and mass-producibility. While the synthesis of large virtual apertures relies on the placement of these elements, the quality of the polarimetric information is determined by the individual element's ability to maintain orthogonal polarization states over a wide field of view (FOV).

Achieving high cross-polarization discrimination (XPD) at millimetre-wave frequencies is notoriously difficult, particularly when constrained by the low-profile, cost-sensitive packaging requirements of the automotive industry. The antenna must not only exhibit robust isolation and gain stability but also mitigate the effects of surface waves and mutual coupling, which can degrade the orthogonality of the MIMO channels. Consequently, the choice of antenna technology is not merely a component selection but a system-level architectural decision that dictates the achievable dynamic range of the polarimetric radar.

3.1 Design requirements and constraints

The transition from standard automotive radar to fully polarimetric imaging imposes a specific set of performance metrics that narrow the field of viable antenna topologies. The primary driver is polarization purity across the scan volume: whereas legacy systems prioritize gain, a polarimetric sensor requires an XPD exceeding 20 dB across a wide azimuth FOV (typically up to ±60°) [4]. This is challenging because the geometric projection of polarization vectors' orthogonality naturally degrades at oblique angles. Find source

Furthermore, these electromagnetic requirements must be reconciled with the realities of automotive integration. The antenna must be compatible with standard multi-layer printed circuit board (PCB) or package-level – typically ball grid array (BGA) or embedded wafer lever BGA (eWLB) – manufacturing processes, usually precluding bulky metallic waveguide flanges or machined horns. Furthermore, mutual coupling becomes a critical parameter in dense MIMO arrays; insufficient isolation between co-located orthogonal ports of dual-polarized antenna elements can lead to signal leakage that is mathematically indistinguishable from target depolarization. Finally, thermal stability is non-negotiable; the phase centre and resonant frequency must remain stable under the harsh temperature cycling of an automotive environment to prevent calibration drift in the virtual array manifold [8].

3.2 Overview of radar front-end technology

The literature presents a diverse array of structural architectures proposed for 79 GHz operation. These can be broadly categorized into planar printed structures – which dominate the current commercial landscape – and substrate-integrated or waveguide-based solutions that offer performance enhancements at the cost of manufacturing complexity.

3.2.1 Planar printed technology

Microstrip antennas. Microstrip patches remain standard technology for commercial automotive radar due to their seamless integration with low-cost multi-layer PCB processes [1]. In polarimetric applications, dual-polarized operation is typically achieved using orthogonal feeds (aperture-coupled or probe-fed) or proximity-coupled patches [9, 10, 11]. While highly manufacturable, patch antennas suffer from intrinsic limitations at microwave frequencies: they are prone to high dielectric loss and surface wave excitation which degrade efficiency and coupling, and their narrow impedance bandwidth can be a bottleneck for wideband chirps [12]. Moreover, maintaining high XPD at wide angles is difficult due to the inevitable cross-polar radiation from the feed lines. Microstrip stub antennas, which utilize shaped stubs for improved impedance bandwidth and polarization control, pose a compelling alternative to conventional series patch arrays for compact, low-profile implementations [13].

Slotted radiation. Slot-based elements, including cavity-backed slots and slanted slot arrays, offer an alternative planar approach. Slots naturally exhibit high polarization purity and can be more robust against mutual coupling than patches [14, 15]. However, they are intrinsically single-polarized, and hence, integrating dual-polarized slot arrays often requires multi-layer feed networks [16] that increase board complexity, and their bidirectional radiation pattern usually necessitates a back-cavity or reflector, adding to the vertical profile.

Thin-film antennas. Thin-film antennas leverage advanced deposition techniques to realize ultra-thin radiating structures directly on the substrate [17]. While thin-film designs can support dual-polarization and flexible integration, they are typically very lossy at millimetre-wave frequencies, which limits their efficiency and practical deployment in automotive radar systems.

3.2.2 Integrated waveguide technology

To overcome the loss mechanisms of microstrip lines, *substrate integrated waveguide* (SIW) and *low temperature co-fired ceramic* (LTCC) technologies confine the electromagnetic field within a synthesized waveguide structure embedded in the dielectric. SIW antennas exhibit significantly lower transmission losses and superior element isolation compared to microstrip [18]. Their enclosed nature provides excellent shielding, making them robust against interference and temperature-induced deformations. However, the requisite via-fencing consumes considerable board real estate, posing a challenge implementing dense MIMO lattices without sacrificing grating lobe performance.

Gap waveguide (GW) and *ridge gap waveguide* (RGW) technologies represent a significant evolution in low-loss millimetre-wave design, addressing the assembly bottlenecks of traditional hollow waveguides. By utilizing an electromagnetic band-gap (EBG) surface, such as the ‘bed of nails’ reported by Kildal et al. [19], to suppress parallel-plate modes, GW technology achieves the low loss of air-filled waveguides while eliminating the requirement for conductive electrical contact between waveguide layers.

This ‘contactless’ characteristic creates a unique advantage for automotive radar: it relaxes the stringent mechanical flatness and assembly torque requirements that drive up the cost of traditional split-block waveguides. While early iterations relied on costly CNC milling, recent advancements in metallized plastic injection moulding and PCB-based implementations (using via fences or mushroom structures) have drastically reduced fabrication costs, as validated in the industrial study by [20]. Consequently, GWs are transitioning from academic demonstrators to commercial viability, offering a robust solution for high-efficiency, fully metallic antenna arrays capable of withstanding the harsh thermal and vibrational environments of automotive sensing [21].

3.2.3 Volumetric antennas

While impractical for conformal automotive integration, *horn antennas* and *dielectric resonator antennas* (DRAs) serve as important benchmarks, hence their use in polarimetric system demonstrators, such as those presented by Tinti et al. [4] and Trummer et al. [22]. Horns exhibit outstanding gain and polarization discrimination but are volumetrically incompatible with bumper-integrated sensors. DRAs offer wide bandwidth and high radiation efficiency by eliminating metallic losses [23], yet they face challenges regarding mechanical robustness and the precision assembly required to mount 3D dielectric blocks onto a planar radar transceiver.

Launcher-in-package technology. In recent years, launcher-in-package (LiP) technology has emerged as a promising solution to the traditional challenges of integrating waveguide antennas with monolithic microwave integrated circuits (MMICs). By embedding the waveguide transition directly within the package substrate, LiP minimizes the number of RF transitions, thereby reducing insertion loss and reflection typically associated with conventional chip-to-waveguide interfaces [24]. While still an emerging technology, this advancement enables more efficient coupling between the transceiver and the antenna, making waveguide-based solutions more viable for compact automotive radar systems [25].

3.3 Comparative analysis of antenna technologies

A critical review of the literature reveals that antenna performance is not determined by a single design choice, but rather by the interaction between two distinct layers: the *radiating element* and the *integration platform*. In many reported designs, these two aspects are conflated. To provide a clearer map of the design space, this analysis decouples these layers, evaluating them separately before synthesizing the state-of-the-art findings.

3.3.1 Radiating element typologies

The choice of radiating element dictates the intrinsic bandwidth, polarization discrimination, and radiation pattern of the sensor. Table 3.1 categorizes the fundamental element types found in automotive radar literature.

While microstrip patches dominate commercial implementations due to their low profile, they are intrinsically narrowband and prone to surface wave excitation. In contrast, volumetric radiators like horns and DRAs offer superior bandwidth and polarization stability but face severe integration penalties. Slot radiators occupy a middle ground, offering high XPD but requiring complex back-cavity structures to suppress bidirectional radiation.

3.3.2 Integration platforms

The integration platform defines the feeding structure of the antenna system: it determines insertion loss, isolation between MIMO channels, and thermal stability. As shown in Table 3.2, the industry standard (microstrip/PCB) trades performance for cost, while academic research heavily favours waveguide-based structures to maximize signal fidelity.

Table 3.1: Comparison of radiating element types for polarimetric radar

Element type	**BW (%)**	**XPD (dB)**	**Profile**	**References**
Edge-fed patch	< 5	15–20	Very low	[26, 27, 28]
Aperture-coupled patch	5–15	20–30	Low	[10, 18, 29, 30, 31]
Microstrip stub	< 5	20–25	Very low	[13, 32]
Thin-film antenna	~ 10	20–30	Very low	[17]
Slotted waveguide	< 5	15–25	Low	[33, 34]
Cavity-backed slot	< 5	> 25	Moderate	[14, 15, 16, 35, 36]
Horn waveguide	> 15	> 25	High (3D)	[4, 22, 37]
Dielectric resonator	10–15	~ 20	High (3D)	[23, 38]

Table 3.2: Comparison of integration and feeding platforms

Platform	**Loss**	**Isolation**	**Complexity**	**References**
Planar PCB	High	Low	Very low	[13, 26, 27, 28, 32]
Multi-layer PCB	Moderate	Moderate	Moderate	[18, 35, 39]
Metallic waveguide	Very low	Very high	Moderate	[4, 14, 22, 40]
SIW	Moderate	High	Moderate	[15, 29, 31, 33, 36, 37]
LTCC	Low	High	High	[34]
Gap waveguide	Low	Very high	High	[12, 41]

3.4 Synthesis of state-of-the-art trends

Analysing the intersection of these element and platform choices reveals a clear dichotomy in the current state of the art.

Industrial baseline. Despite their electromagnetic limitations, microstrip patch arrays remain the incumbent solution for mass-market automotive radar. The manufacturing maturity of standard PCB processes allows for the low-cost integration of complex series-fed or series-parallel networks directly alongside the MMIC [42]. However, for polarimetric applications, this convenience comes at a cost: standard patches struggle to maintain XPD beyond $\pm 30°$ scan angles [36], and the mutual coupling between closely spaced elements in a dense MIMO array introduces phase errors that degrade virtual aperture synthesis and the performance of signal processing algorithms, as explored by Arnold and Jensen [43].

Performance frontier. Recent academic literature identifies GW and RGW as the primary candidates for overcoming the inherent dielectric losses and surface-wave coupling of high-frequency PCB technology. By creating a prohibiting EBG, GW structures suppress parallel-plate modes entirely without requiring a galvanic connection between the waveguide layers. This 'contactless' property is a critical industrial enabler; it significantly relaxes the mechanical assembly tolerances that make traditional hollow waveguides cost-prohibitive for high-volume production. Through the adoption of metallized injection moulding and high-precision plastic stamping, the manufacturing complexity is shifted from individual assembly to the mould-design phase, allowing for the low-cost mass production of air-filled structures. Consequently, GW technology, particularly in combination with the LiP technology, represents the emerging 'gold standard' for next-generation MIMO arrays, providing the polarimetric fidelity and thermal robustness required for high-resolution automotive sensing within a commercially viable form factor [44].

The compromise. SIW architectures effectively bridge the gap between planar and volumetric designs. By synthesizing a dielectric-filled waveguide using periodic via fences, SIW provides the electromagnetic shielding and low-loss characteristics of metallic waveguides while retaining the manufacturability of standard PCBs. The versatility of this platform is exemplified by Zhao et al. [37], who demonstrated that multi-layer PCB stacks can be used to synthesize quasi-pyramidal horn antennas entirely within the substrate.

Furthermore, the layered structure of SIW facilitates advanced hybrid topologies. For instance, designs by Puskely et al. [29] and Yang et al. [36] combine the isolation benefits of an integrated waveguide feed with the beam-shaping flexibility of printed elements, using coupling slots in a sandwiched ground layer to excite parasitic patches on the surface.

In parallel, LTCC technology offers a similar volumetric approach but with superior thermal stability and dimensional tolerance compared to organic substrates, making it attractive for highly integrated package-level antennas, albeit at a higher implementation cost.

3.5 Emerging paradigms

Beyond the established categories of printed and waveguide-based elements, several exploratory technologies are expanding the design space for automotive radar. These paradigms prioritize the synthesis of ideal radiation characteristics over traditional fabrication constraints.

Magneto-electric dipoles (MED). Originally developed to overcome the narrow bandwidth of standard patch antennas, the magneto-electric dipole has recently been adapted for millimetre-wave radar to address the specific requirements of polarimetric fidelity. By combining a planar electric dipole with a complementary magnetic dipole (typically synthesized via shorted patches or via-fenced slots), MEDs function effectively as Huygens sources.

This complementary excitation yields two distinct advantages for automotive sensing. First, it achieves wide impedance bandwidths (usually $> 20\,\%$), easily covering the full 76 GHz to 81 GHz band required for high-resolution 4D imaging [45]. Second, and more critically for polarimetry, MEDs exhibit nearly identical E- and H-plane radiation patterns with low cross-polarization. This pattern symmetry ensures that the radar's 'view' of a target is consistent regardless of polarization orientation, potentially simplifying the calibration matrices required for precise direction-of-arrival (DOA) estimation.

Metasurface-enhanced isolation. As MIMO arrays become denser to support higher angular resolution, mutual coupling via surface waves becomes a dominant source of error. Designers are increasingly leveraging metasurfaces – periodic sub-wavelength structures etched into the PCB ground or top layer – to manipulate these boundary conditions.

Rather than functioning as radiating elements themselves, these structures often act as EBG filters or soft surfaces. By presenting a high surface impedance to grazing waves, they effectively trap or dissipate surface currents between adjacent patch elements. Recent implementations have demonstrated isolation improvements of 10 dB to 20 dB with negligible impact on the primary radiation pattern, offering a planar solution to the coupling problems that traditionally required metallic wall isolation [46].

Additive manufacturing and 3D lensing. With recent advances in high-precision 3D-printing technology, such as stereolithography, additive manufacturing for millimetre-wave components is enabling geometries previously impossible to manufacture via moulding or machining. The primary application in automotive radar is the *integrated lens antenna* [47]. Instead of mounting a separate plastic lens, 3D printing allows for the fabrication of Luneburg or Maxwell fish-eye lenses directly onto the antenna aperture or package.

While this offers a path toward 'volumetric' gain performance within a conformal footprint, the technology faces a steep material science barrier: most printable photopolymers exhibit relatively high loss tangents ($\tan(\delta) > 0.01$) at 79 GHz. Furthermore, the surface roughness inherent to layered printing can introduce phase errors and scattering losses, necessitating post-processing steps that currently limit mass-market scalability.

3.6 Design implications

Finish. Adapt based on Fujikura's preferences?

The survey of the literature leads to a specific set of design imperatives for the polarimetric MIMO demonstrator targeted in this work. While *gap waveguide* technology offers the highest theoretical performance – specifically regarding the critical metrics of XPD and mutual coupling – its fabrication complexity poses a risk for rapid prototyping. Conversely, *microstrip patches* offer a low-risk, low-cost baseline but are likely to bottleneck the polarimetric dynamic range of the system.

Therefore, a pragmatic high-performance approach points toward *SIW-based topologies* or *advanced cavity-backed slot* designs. These architectures offer the requisite isolation and polarization stability to validate sparse polarimetric MIMO algorithms, while remaining within the bounds of standard PCB fabrication capabilities.

Chapter 4

MIMO array design

Existing MIMO array designs for automotive radar predominantly use linear or planar layouts optimized for angular resolution and cost-efficient implementation [48]. TDM-MIMO architectures dominate current commercial systems, typically leveraging 3–4 transmitters with 4–8 receivers to synthesize virtual arrays of 12–32 channels, possibly cascading multiple such modules [49]. Recent research explores sparse 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 systems has been successfully carried over to radar technology, the problem formulation is adapted: in telecommunications jargon, the primary goal of radar is to precise estimate the channel matrix, which encapsulates the desired information about propagation effects, such as time delay, Doppler shift, and angle of arrival, allowing for extraction of target range, velocity, azimuth, and angular position [50, 51]. 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 *co-located* and *distributed* MIMO, as extensively discussed in [52, 53].

Lastly, it should be noted that the transfer of MIMO concepts from communications to radar must be undertaken with care, respecting and integrating the existing knowledge of traditional radar technology. Uncritical adaptation can lead to flawed conclusions, as seen in some early distributed MIMO literature, where certain contributions were either redundant rediscoveries of multistatic radar concepts or contained incorrect statements, as notes by Chernyak [54].

From the standpoint of antenna array design, the key feature of MIMO radar is the creation of a *virtual array* through the combination of multiple transmit and receive antennas. Mathematically, if an array has N_{TX} transmitters and N_{RX} receivers, and each transmitter emits an orthogonal waveform, the received signals can be separated and associated with each transmit-receive pair. This effectively synthesizes $N_{\mathrm{TX}} \times N_{\mathrm{RX}}$ virtual elements, whose positions are determined by the sum (or, in some cases, the difference) of the physical locations of the transmit and receive antennas [55]. The resulting virtual array, which can be obtained as a convolution of the physical transmit and receive element positions, can have a larger aperture and finer angular resolution than the physical arrays alone, but the spatial distribution of these virtual elements depends on both the physical layout and the multiplexing scheme.

Co-located and distributed MIMO radar. A crucial distinction exists between these two configurations. co-located MIMO radar systems feature transmit and receive antennas placed in proximity, enabling coherent transmission and detection. This coherence allows for the formation of a virtual array with enhanced angular resolution and supports advanced adaptive processing techniques. In contrast, distributed MIMO radar systems employ widely separated antennas, a technique known from multi-static radar, emphasizing on spatial diversity gain. This diversity is particularly beneficial for overcoming target scintillation (i.e. fluctuations in radar cross-section) and for improving detection performance in complex environments.

Notably, research was carried out to also explore hybrid approaches that combine the benefits of both co-located and distributed MIMO. For example, Xu and Li [56] discuss systems that leverage both coherent processing and spatial diversity, highlighting the following advantages:

- *Spatial diversity:* Widely-separated antennas in distributed MIMO configurations help mitigate target scintillation and improve detection reliability.
- *Flexible transmit beampattern design:* co-located MIMO enables optimization of the transmit covariance matrix, allowing power to be focused in directions of interest while minimizing correlation of backscattered signals. This leads to significant improvements in adaptive processing techniques.
- *Enhanced resolution and clutter rejection:* The MIMO radar scheme can achieve higher spatial resolution and improved clutter suppression compared to conventional radar systems.

The concept of combining several widely separated subarrays with each subarray containing closely spaced antennas is nowadays often implemented via *multi-aperture multiplexing* and has been successfully applied in *cooperative automotive radars*, improving angular resolution and field of view [57].

Array architectures. A central theme in MIMO radar design is the trade-off between spatial diversity, coherent processing gain, and hardware complexity, which is reflected in the three principal array architectures: fully diverse MIMO, phased arrays, and hybrid MIMO topologies.

In a fully diverse MIMO configuration, each antenna element operates independently, transmitting and receiving orthogonal waveforms. This maximizes spatial diversity and enables robust target detection in complex environments. Mathematically, the transmit covariance matrix in this case is full-rank, reflecting the linear independence of the transmitted signals. However, this requires a separate RF processing chain for each element, increasing hardware cost and complexity.

Phased arrays, in contrast, employ coherent waveforms across all elements, with a common signal distributed via a beamforming network. This approach enables electronic beam steering and coherent processing gain, but sacrifices spatial diversity since all elements transmit the same signal. The transmit covariance matrix is fully degenerate (rank 1), as all signals are linearly dependent.

Many modern systems adopt a hybrid approach, first introduced and called 'phased-MIMO radar' by Hassanien and Vorobyov [58], which combines aspects of both fully diverse MIMO and phased arrays. In these systems, groups of antenna elements form subarrays that transmit coherent waveforms, while different subarrays operate independently with orthogonal signals. The resulting transmit covariance matrix has rank between 1 and full, depending on the degree of the so-called *waveform diversity*. This design balances the benefits of spatial diversity and coherent processing, while managing hardware complexity. The optimization of subarray partitioning and waveform assignment typically leads to a difficult, non-convex optimization problem, as discussed in the research area of *beampattern synthesis*.

4.2 MIMO topologies

The concept of *MIMO topology* can be defined as a mapping from the physical arrangement of transmit and receive antennas, together with the chosen multiplexing scheme, such as time-, frequency-, and code-division, onto the resulting virtual array. This mapping determines the positions and spacings of the virtual elements, which can be uniform or non-uniform depending on the physical geometry and the multiplexing strategy. Non-uniform virtual element spacing can lead to grating lobes, ambiguities, or degraded performance, making the design of the physical and virtual topology a critical aspect of MIMO radar engineering.

Definitions & figures of merit. The MIMO design problem can be formalized as follows: given a desired virtual array configuration (e.g. uniform linear array with specific aperture and element spacing), determine the physical transmit and receive antenna placements and the multiplexing scheme that will synthesize this virtual array. Key figures of merit for evaluating MIMO topologies include:

- *Virtual aperture:* Set of unique transmitter-receiver channels in the resulting virtual array. The aperture is often evaluated as the overall size of the virtual array, corresponding directly to the resulting *angular resolution*.
- *Field of view (FOV):* The angular region over which the array can reliably detect and resolve targets, determined by the physical and virtual array geometry and element spacing.
- *Degrees of freedom:* The number of independent channels available for signal processing, which influences the ability to perform tasks like *direction-of-arrival estimation* and *parameter identifiability*.
- *Element spacing:* The spacing between virtual elements, affecting *grating lobes* and *ambiguity*, especially in sparse layout, where the Shannon-Nyquist spatial sampling criterion is deliberately violated.
- *Side-lobe level (SLL):* The level of side-lobes in the virtual array's beampattern, impacting *clutter rejection* and *target detection*.
- *Mutual coupling:* The interaction between physical elements, which can distort the intended virtual array response, leading to *errors in angle estimation* or *degraded detection performance*.
- *Implementation complexity:* The practical feasibility of the physical layout and multiplexing scheme, considering hardware constraints.

4.2.1 Application requirements

The synthesis of MIMO topologies is fundamentally dictated by the sensing scenario, making application requirements the primary driver of array design. For automotive radar, the ability to resolve targets in both azimuth and elevation is essential, necessitating two-dimensional (2D) aperture extension. Modern front-looking automotive radar sensors, as described by Waldschmidt et al. [1], require a wide azimuth FOV of approximately $\pm 30°$ to $\pm 60°$ and a moderate elevation FOV of about $\pm 15°$ to $\pm 30°$. These requirements exceed what can be achieved with simple non-uniform elevation extensions of moderate-aperture linear arrays, necessitating employment of either a large element count or sparse array techniques.

However, synthesizing optimal 2D virtual arrays is challenging: the number of possible transmit-receive combinations increases rapidly, and the synthesis remains a non-deterministic optimization problem with no general closed-form solution for constructing a virtual array with ideal properties from a fixed set of physical elements. This combinatorial complexity – combined with practical constraints such as hardware cost, mutual coupling, and calibration – makes 2D MIMO topology synthesis a challenging and active research area [59].

In automotive radar, practical constraints such as limited sensor footprint and integration requirements restrict MIMO implementations almost exclusively to co-located array configurations. This spatial constraint is a systemic requirement imposed by the compact form factors and mounting locations typical of automotive platforms. As a result, the theoretical advantages of distributed MIMO – such as enhanced spatial diversity – are generally unattainable in this context.

The signal processing benefits of co-located MIMO for automotive radar are now well-established. These include the synthesis of large virtual arrays, improved angular resolution, and the ability to apply advanced adaptive processing techniques. The literature provides a comprehensive treatment of these advantages, with concepts such as parameter identifiability [60] and virtual aperture extension [61] serving as key metrics for system evaluation. The maturity of the field is further underscored by the availability of specialized reference texts dedicated to MIMO radar theory and practice [62].

Despite significant progress, two major challenges remain. First, the analytical synthesis of optimal 2D virtual arrays is still underdeveloped, leaving most practical designs reliant on numerical optimization or empirical patterns. Second, there is a pressing need to bridge the gap between electromagnetic phenomena—such as mutual coupling and parasitic effects—and signal processing algorithms, as these physical realities can introduce errors that degrade radar performance. Addressing these challenges is essential for advancing both the theoretical and practical capabilities of automotive MIMO radar.

4.2.2 Topology synthesis methods

The synthesis of MIMO array topologies is a mature field offering a spectrum of design methodologies, spanning rigid analytical constructions and flexible numerical optimization techniques. Analytical approaches, particularly those governing uniform linear arrays and uniform planar arrays, provide closed-form solutions and valuable insight into the mapping between physical and virtual array geometries, typically derived using the concept of the *difference co-array* [63]. While these deterministic designs offer predictable phase centres and well-characterized point spread functions, they are often limited to specific configurations and may not generalize to constrained automotive scenarios.

For more intricate designs – such as non-uniform or highly sparse arrays, or when practical constraints like packaging and mutual coupling must be considered – numerical optimization becomes essential. In these cases, the synthesis problem is formulated using an objective function that encodes key figures of merit, including virtual aperture, side-lobe level, and ambiguity [64]. Optimization algorithms employed in this context range from evolutionary heuristics (such as genetic algorithms, simulated annealing, and differential evolution) to modern convex relaxation methods, iteratively exploring the design space to reveal Pareto-optimal trade-offs between angular resolution and side-lobe suppression [65]. However, the resulting 'exotic' geometries often lack translational invariance and introduce significant implementation challenges, particularly in terms of manifold calibration and mutual coupling compensation. These practical difficulties can obscure the validation of novel signal processing chains, as most optimization-driven designs assume idealized, minimum-scattering antennas – an assumption that does not hold in real-world applications and can lead to degraded processing algorithm performance [43].

Topology classes for automotive radar. When considering MIMO topologies for automotive applications, it is crucial to recognize the distinction between theoretical sparse concepts and industrially deployable classes.

The most established class is the uniform linear array and its two-dimensional extension, the uniform planar array. These arrays feature regularly spaced elements – typically at half-wavelength intervals ($d = \lambda/2$) – resulting in an ambiguity-free field of view and direct compatibility with standard fast Fourier transform (FFT) algorithms. Their regularity is particularly advantageous for polarimetric research; it minimizes phase centre mismatch errors that can otherwise corrupt the delicate phase relationships between horizontal and vertical polarization channels. While the scalability of uniform arrays is limited by the proportional increase in hardware cost, they provide the most controlled environment for isolating and characterizing Doppler-resolved polarimetric signatures.

To address the aperture limitations of uniform arrays, structured sparse arrays have emerged as the current state-of-the-art in deployed automotive imaging radar (e.g. cascaded chipsets). Unlike the random or highly irregular sparse arrays found in theoretical literature, industrially supported sparse designs rely on specific, repeatable patterns to extend the virtual aperture. These designs offer a pragmatic compromise: they achieve the improved angular resolution necessary for modern sensing while maintaining enough structural regularity to be reliably calibrated in mass production.

Selection rationale. In summary, while the academic literature is rich with novel, optimization-driven antenna concepts, the development of robust polarimetric processing algorithms benefits from a stable hardware baseline. By utilizing established uniform topologies or industry-standard sparse reference designs, system variability is minimized. This ensures that observed anomalies in the Doppler-polarimetric domain can be attributed to target scattering physics rather than artefacts of an experimental antenna array manifold.

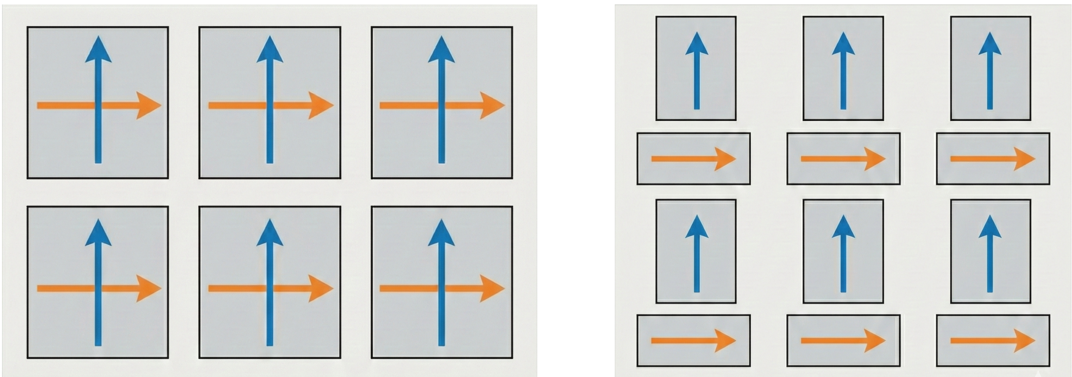
4.3 Polarimetric MIMO topology

The integration of polarimetric functionality into MIMO radar introduces a new dimension to topology synthesis: the management of the dual-polarized signal space. Unlike scalar MIMO (one polarization), where the primary goal is maximizing the virtual aperture, polarimetric designs must also ensure the fidelity of the full scattering matrix measurement. Consequently, the design space splits into two fundamental architectural choices: the use of dual-polarized elements sharing a common phase centre versus the spatial interleaving of single-polarized elements.

Dual-polarized architectures. The most theoretically robust approach involves the use of dual-polarized elements at each array position (see Figure 4.1a). In this configuration, orthogonal polarizations (typically horizontal and vertical) share a common phase centre. The primary advantage of this topology is the maximization of the virtual aperture for all polarization channels simultaneously, ensuring that the polarimetric scattering matrix is measured from an identical spatial perspective. This eliminates the 'polarization squint' effects caused by viewing a target from slightly different angles, thereby simplifying the calibration process.

However, this electromagnetic ideal comes with significant implementation penalties. Dual-polarized patch antennas or horn feeds require complex feeding networks, often necessitating orthogonal mode transducers (OMTs) or multilayer substrates that increase the physical bulk of the sensor. Furthermore, maintaining high isolation between the co-located channels is challenging; the proximity of the feeds invariably leads to increased mutual coupling and cross-polar leakage, which can corrupt the delicate polarimetric signature of the target.

Interleaved single-polarized architectures. To mitigate the hardware complexity and coupling issues of co-located designs, an alternative strategy is to spatially interleave single-polarized elements (see Figure 4.1b). By spatially separating the horizontal and vertical elements, this architecture inherently improves port-to-port isolation and simplifies the routing of feed lines. While this reduces the cost and complexity of the PCB stack-up, it introduces a spatial disparity between the polarization channels. If not carefully compensated for in the manifold synthesis, this phase centre mismatch can lead to angle-dependent polarization errors, particularly for near-field targets or distributed scatterers.



(a) Dual-polarized elements

(b) Interleaved single-polarized elements

Figure 4.1: Comparison of physical element arrangements for polarimetric MIMO radar.

Virtual channel overlapping. A hybrid design strategy, which is worthy of investigation, is the exploitation of MIMO virtual array synthesis to bridge the gap between these two architectures. It is hypothesized that by carefully designing the overlapping patterns of transmitting and receiving sub-arrays, one can synthesize specific *virtual* positions where the co- and cross-polar channels coincide purely through signal processing, even if the physical elements are spatially separated.

This concept is illustrated in Figure 4.2. By ensuring that specific indices of the virtual convolution overlap, the system can provide 'anchor points' of true polarimetric alignment. These overlapping virtual phase centres could potentially serve as a high-fidelity reference for polarimetric calibration – effectively simulating the performance of a dual-polarized element – while retaining the manufacturing simplicity and isolation benefits of a single-polarized interleaved layout.

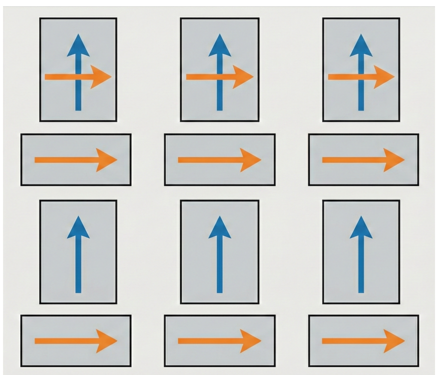


Figure 4.2: Overlapping channels in an interleaved single-polarized element grid

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. [66]: First people to perform vehicular target classification on pre-detection data.
  - Tilly et al. [67]: 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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