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Wideband MIMO Rooftop Antenna for Vehicular Communication Systems, A Literature Survey and Design Gap Analysis

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Abstract - Modern vehicles carry LTE/5G, cellular-V2X, DSRC, GNSS and Wi-Fi radios, most of them inside one roof-mounted shark-fin. The review ends with a design direction and a test plan that's crediting the lines only with what they add over the module's own decoupling. Neutralization lines are well recorded for narrow bands on phone-sized boards, but none of the papers reviewed shows one decoupling a 617 MHz to 6 GHz vehicular antenna. Every need is met by none of the reviewed designs. Twenty-one references are checked against a design brief modelled on a published four-element module: four elements on a 175 × 75 mm ground plane, a height below 20 mm, and a GNSS notch. The only reviewed design under 20 mm is that four-port module, which gives about 10 dB of low-band isolation, efficiency below 30% and no stated full-band coverage or notch, while the designs with better isolation are 28 to 30 mm tall and port. 617 MHz must be covered to 6 GHz by a small housing, protect the GNSS band, and keep several MIMO ports from coupling into each other; this paper reviews the closest published work: shark-fin MIMO antennas, rooftop-cavity alternatives, and mutual-coupling reduction methods.

Key Words, namely vehicular antenna, MIMO, V2X, wideband PIFA, mutual coupling, GNSS notch.

1. INTRODUCTION

A car roof today does more radio work than most people realize. Long-Term Evolution (LTE) and fifth-generation (5G) networks are needing continuous coverage from 617 MHz up to the mid-band 5G allocations, cellular vehicle-to-everything (V2X) links and dedicated short-range communication (DSRC, IEEE 802.11p) both work around 5.9 GHz, the global navigation satellite system (GNSS) needs its own quiet band around 1.2-1.6 GHz, and Wi-Fi adds another 2.4/5 GHz pair on top, on the whole. All of it has ordinarily gone into the shark-fin, the small fin-shaped housing bolted to the rear of the roof, in actual application.

That housing is starting to run out of room. Panoramic glass roofs, roof-mounted light detection and ranging (LiDAR) and camera pods, and increasingly aerodynamic styling all compete for the same real estate the shark-fin employed to have to itself, at least in principle. One line of research responds by pushing more radiators into the same small volume with better decoupling; a second, smaller line is arguing for scrapping the fin altogether and building a larger antenna cavity into the roof structure, at least empirically. Both strands matter for a multiple-input multiple-output (MIMO) antenna aimed at 617 MHz - 6 GHz; this paper is reading them together, because a design choice in one strand (say, cavity size) directly is changing what's achievable in the other (say, isolation from spacing alone).

What gets in the way is generally one of size; the band from 617 MHz to 6 GHz has a fractional bandwidth of about 163%, in many respects. What's more, a free-space wavelength of 486 mm is had by the lowest frequency, at least in practice; in fact, fitting a radiator for that wavelength into a housing a few centimetres tall, four times, with every pair of ports separated from every other pair, is the core problem. Numbers are put on it by section 3.2.

The review was, more precisely, put together to support a final-year design project, like a four-element wideband MIMO antenna on a 175 × 75 mm ground plane, with a height below 20 mm, a GNSS notch, and neutralisation-line decoupling, to a significant degree. The project is modelled on the four-element module of Michel et al. [1], which was built for locations such as, under the dashboard or inside the rear spoiler, all things considered. And it's keeping that module's board size. The gaps reported here are therefore gaps against this brief, not against every possible vehicle installation, in the main. All we want is mainly to keep the form of that module and sharpen what it gives up, like its low-band isolation and efficiency, and its unstated full-band coverage and GNSS behavior, broadly speaking. A roof cavity (Sec. 2.3) is a possible later stage.

The contributions of this paper are a comparison of twenty-one references against one explicit design brief, a statement of what spacing alone achieves at the low band, a statement of what the neutralization-line literature does and doesn't show for this band, and a test plan that's following from them, in real-world scenarios. Section 2 reviews the literature, Sec. 3 describes the method, the brief and the metrics, Sec. 4 presents the comparison and the gaps, Sec. 5 discusses the design direction, the verification plan and the limits of the review, and Sec. 6 is concluding, at least for now. The introduction and methods are being followed by the paper, especially regarding results, particularly for discussion (IMRaD) structure.

2. LITERATURE REVIEW

This review is made up by three overlapping groups of published work. The second is the rooftop-cavity idea, where the antenna sits in a large cavity built into the roof, and other low-profile locations such as the dashboard and the rear spoiler, at least empirically. The first is MIMO antennas made for the standard shark-fin housing, covering part or all of the 617 MHz - 6 GHz range, to a significant degree. The third is mutual-coupling and isolation techniques, meaning the methods that are keeping two closely spaced elements from interfering with each other.

2.1 Background: Time, Size and Ground Plane

Two physical facts are framing everything that's following; small antennas are bandwidth-limited. Chu showed the quality factor of an antenna has a lower bound set by its electrical size, so the smaller the volume that encloses the antenna relative to the wavelength, the narrower the bandwidth it can have [2], broadly speaking; and thus, a housing 20 mm high is about 0.04 λ at 617 MHz (Table 5), which is very small for a band that

must also stretch to 6 GHz, in actual application. And then, at the low end the ground plane is part of the antenna. Below about 1 GHz, a monopole or planar inverted-F antenna (PIFA) mounted on a board only a fraction of a wavelength long excites currents on that board, so the board dimensions are changing the resonance, the pattern and the coupling between ports [3]; okay then shark-fin designs are, in practice, measured on a one-metre plane or on a roof. What's more, why don't their findings transfer directly to a small board.

The PIFA and the folded monopole are, as a matter of fact, the two usual ways of coping with these limits, on the whole. A PIFA is a radiating plate held above the ground plane and shorted to it at one edge, so the current path is needing to be only about a quarter of a wavelength, and that path can be folded or meandered to fit the available volume, to a significant degree. A folded monopole is, to be sure, reaching the same end by bending its length into a compact three-dimensional shape; in fact, both trade height for horizontal area, and the horizontal area is usually restricted by the size of the housing, which is currently why height and size have to be found together.

2.2 Wideband MIMO Antennas for the Shark-Fin Housing

Yacoub, Khalifa and Aloi [4] are the full-band reference point for this project, and their low-profile PIFA is cut from a metal sheet 28 mm high, 55 mm long and 50 mm wide, covers 617 MHz to 6 GHz, and acceptably rejects in the GNSS bands, on the whole. Two-element MIMO systems were then built from this PIFA and a companion monopole [5] by the same group, using spatial, rotational and orthogonal arrangements of the elements, at least for now. Both papers measured on a one-metre ground plane and on a vehicle roof, not on a board the size of this project's. The 28 mm height is the number this project has to deal with, since the target ceiling is 20 mm; and thus, in the system with two PIFAs placed about 120 mm apart (0.25 λ at 617 MHz), isolation is around 11 dB at the low band, the envelope correlation coefficient (ECC) is below 0.39, diversity gain (DG) is above 9.2 dB. As, well, port efficiency is above 60% on a vehicle [5], and isolation there comes from placement and orientation, not from a decoupling structure.

Khalifa, Yacoub and Aloi [6] built three MIMO systems from one branched monopole element - two 2×2 layouts with opposite element orientations, broadly speaking. One 4×4 layout. 617 MHz is covered to 5 GHz by the frameworks, fit up to four elements in one shark-fin, and were measured on a one-metre ground plane and on a vehicle roof, with isolation, ECC and diversity gain reported for each layout, at least in principle; and thus, more elements mean more impact area, so these systems are saying little about a tight envelope.

Ibrahim, Yacoub and Aloi [7] took a separate route, like a three-dimensional monopole with two branches, made to fit inside a roof-top shark-fin, all things considered. The lower cellular band is covered from 617 to 960 MHz by the long branch, in many respects; what's more, the short branch is covering 1559 to 6000 MHz, which includes the upper GNSS band (1559-1606 MHz) and the 5.9 GHz V2X band. Not ever mind, the antenna is 58 mm tall, 37 mm long and 17 mm wide, at least in principle; in fact, as, well, it was measured on a one-metre ground plane and on a vehicle roof, with a maximum measured efficiency of 88% at 787 MHz, in real-world scenarios. The impact area is small, but the 58 mm height is nowhere near the 20 mm ceiling; it's a single-feed element, not a MIMO pair, so no isolation figure employs; it also receives GNSS rather of rejecting it, and but still, it isn't a model for the notch. Abdul-Rahman and Aloi [8], from the same research group, use characteristic mode analysis to get a consistent radiation pattern, across 0.617-5 GHz from a akin long-structure/short-structure monopole; its principal value is, broadly speaking, as a worked example of why the branch dimensions behave the way they do. An element height of about 58 mm is still used by the design, inside a shark-fin limited to 70 mm in total, so it doesn't help with the height limit.

Two earlier designs from the same group are showing what's already known. A person monopole covering 617 MHz to 5 GHz with reasonable rejection of the L1, L2 and L5 GNSS bands was measured on a one-metre ground plane and on a vehicle roof [9], in real-world scenarios. A two-element MIMO pair of raised printed monopoles on FR4 with a partial ground plane is covering only 1.71 to 5 GHz, and was measured on a one-metre rolled-edge ground plane [10]. The first design is suggesting that GNSS rejection can be built into one wideband element. The second indicates that a two-element pair is much easier once the low band is left out: the MIMO systems of this group that do reach 617 MHz are the PIFA and branched-monopole systems of [5] and [6].

The most recent entry in this line, Ding et al. [11], is packing five radiators into a 90 × 15 × 30 mm³ shark-fin; two mirrored PIFAs are covering 0.68-6.05 GHz (reflection coefficient S11 below -6 dB), and a frequency-modulation (FM) radio radiator sits between them as a spatial coupling blocker, not as a separate decoupling network, broadly speaking. Widening the gap between the two PIFAs from 10 mm to 22 mm already took simulated isolation above 16 dB; the FM element then pushed it above 20 dB, across the range and below -30 dB over most frequencies, all things considered. Measured isolation between the two cellular ports stays better than 17 dB from 0.5 to 6 GHz (better than 15 dB for every port pair, including the Wi-Fi element), measured efficiency stays above 60%, and ECC is below 0.085; two warnings matter for this project, such as the band is starting at 680 MHz, not 617 MHz, and the -6 dB standard is looser than the usual -10 dB. The PIFAs are 30 mm tall, slightly taller than the 28 mm element in [4], but the isolation mechanism, a architecture inserted between two elements, is directly pertinent to a neutralisation-line strategy even though the geometry differs.

Read together, a pattern is shown by these papers; in turn, for this band the PIFA designs ([4], [11]) are 28 to 30 mm tall, in actual application, and the monopole designs ([7], [8]) are about 58 mm tall, so the PIFA family is roughly half the height of the monopole family, plus neither comes close to 20 mm, on the whole. For a height-limited project the PIFA is therefore the natural starting point, which is why plus, the question becomes how much further its height can be compressed.

2.3 Rooftop Cavity and Other Low-Profile Locations

A separate and considerably smaller line of research, mostly from one group at TU Wien and TU Ilmenau, is arguing for dropping the shark-fin altogether, in real-world scenarios. Artner, Kotterman, Del Galdo and Hein [12] built three antenna modules, a cavity above the windscreen, a chassis cavity in the roof centre and a shelf at the rear, into a sedan-type car mock-up and characterised each with a wideband conical monopole from 0.85 to 6 GHz, on the whole. The headline result is isolation: with neighbouring modules at least 62 cm apart, the worst coupling was 26 dB between centre and rear, and 35 dB or better between front and rear, which the authors call almost unachievable in a shark-fin; the shark-fin modules they're mentioning reached about 6 to 10 dB near 1 GHz [12]. Artner's earlier work on a carbon-fibre-reinforced plastic (CFRP) cavity [13] showed the cavity can be manufactured as part of the chassis itself, with near-omnidirectional radiation measured

from 2 to 6 GHz, and a later cavity built into the roof of a sedan [14] increased coverage toward the driving direction.

Before proof is also collected by the same paper that spacing matters on vehicles, at least in principle. MIMO channel measurements indicate that spatial diversity is more applicable than polarization diversity on vehicles, in the main. As, well, 15% higher throughput was found by a drive test when two antennas were moved from one shark-fin to the left and right sides of the roof [12]. All i mean is the val for the cavity approach. What's more, it's also the reason a fixed footprint is hard - the strongest isolation results in this field are bought with distance.

The trade-off is fabrication. An actual cut-out in a roof panel, or is being needed by a cavity design a roof mock-up built to represent one, in many respects; a shark-fin design can be checked on a flat 1 m ground plane or bolted onto a roof with adhesive, to a significant degree. The prototype in [12] needed the roof of the mock-up to be cut open, and chassis-cavity integration is therefore left for a later phase; the 175 × 75 mm board and a height below 20 mm stay the binding spec for now.

Not every low-profile design stays on the roof. What's more, a folded metal sheet adds the low-band resonance. What's more, each element fits in a 19.1 × 15 × 65 mm box; in turn, part of each element is printed on the PCB, at least in principle. A four-element LTE/5G module for the dashboard or the rear spoiler, where element height has to stay, under Michel built the about 2 cm, Singh and Nepa [1], at least in principle. The module measures 175 × 75 × 19.1 mm on a 1.6 mm printed circuit board (PCB). Isolation between the two elements on each short edge was a obstacle, so the authors added a lossy lumped decoupling network; it raised the worst-case low-band isolation (below 1 GHz) from about 4 dB to 10 dB, but efficiency, already under 30% at the low band, dropped further. The paper doesn't state coverage over the full 617 MHz - 6 GHz range; it doesn't report a GNSS notch. S11 stays below -6 dB across the cellular bands. And more, the imitated ECC is below 0.18 under 1 GHz and below 0.1 above 1.7 GHz; this project is modelled on this module and keeps its board size and a height below 20 mm.

2.4 Mutual Coupling and Isolation Techniques

2.4.1 Technique families

MIMO elements inside a shark-fin sit only millimetres to centimetres apart, so a whole body of work exists just on keeping them from interfering, in the main; the survey by Al-tameemi et al. [15] is grouping the published schemes into the neutralisation lines, metamaterials (electromagnetic band gap structures and metasurfaces), parasitic elements, defected ground structures (DGS), decoupling networks, and hybrids of these, broadly speaking. 5G-band designs are, indeed, covered in broad by the survey and isn't precise to vehicles; slots in the shared ground plane are, for all practical purposes, cut by defected ground structures to break up the surface-current path. Neutralisation lines are normally thin doing strips that carry a current to cancel the coupled current between two elements.

2.4.2 Neutralisation lines

The neutralisation line deserves a closer look, because the suggested design rests on it, in many respects. Later on, bandwidth: a line is canceling coupling that changes with frequency, and the wideband version of Zhang and Pedersen [17] was shown on an ultra-wideband antenna (UWB, which is starting at 3.1 GHz) with a 35 × 16 mm clearance area, far from a 617 MHz low band, at least empirically. Among the papers reviewed here, none is showing a neutralisation line decoupling a 617 MHz - 6 GHz vehicular antenna. Two limits matter here. Diallo et al. [16] placed two PIFAs on a phone-sized ground plane and inserted a suspended line between their feeds and/or shorting points to maximise isolation, and they checked the strategy with a few prototypes. To start with up, the finding rests on the board, such as Addaci et al. [3] showed the isolation of two closely spaced PIFAs, with and without a neutralisation line, differs periodically with ground-plane length, with a coupling minimum at 55 mm (0.38 λ) in their case, so a result can't be carried to a distinct board without re-tuning. The idea comes from mobile-phone work.

2.4.3 Recent V2X examples

One V2X example is worth reading closely, and is combining an absorber wall with a combline filter [18], in actual application; both are working only around those frequencies, so neither tackles the 617 MHz - 6 GHz problem, but they support employing placement and orientation before adding any architecture, at least empirically. Together isolation is being pushed past 37 by them dB with an ECC below 0.005, with the filter centred at 4 GHz; indeed, a quad-port dual-band design for 3.5 and 5.9 GHz [19] shows how far element orientation alone can go, namely four orthogonal elements, 7 mm apart, reach isolation above 20 dB and ECC below 0.03 with no decoupling structure at all. The wall is decreasing radiated coupling between beside antennas, and the filter, placed between their grounds, handles coupling through the ground plane.

2.4.4 A working order

From these papers a working order for a space-constrained design is drawn; this order is our own reading, not a rule stated in any person paper. Use element placement and orientation first, since they add no parts; that said, spacing is only free when the size has room for it; add a passive arrangement (neutralisation line, DGS, or an inserted third element as in [11]) where placement alone can't get isolation into an acceptable range; and keep metasurface-based or lossy-network decoupling for cases where neither of the first two is enough; this is the logic that shapes the direction taken in Sec. 5.2.

2.5 Summary of the Literature

Four statements are being supported by the reviewed literature, and wideband coverage from 617 MHz to 6 GHz inside one shark-fin is established; that said, it takes 28 to 30 mm of height for two ports [4], [5], [11] and 58 mm for one [7], on the whole. Roof-cavity spacing bestly separates, 26 to 35 dB [12]; in turn, though, it's needing several roof locations and a cut roof, in actual application; what we lack is the combination of these, such as four ports, the full band, a stated GNSS notch and valuable low-band isolation, all under 20 mm. A four-element module under 20 mm exists [1], with about 10 dB of isolation and efficiency under 30% at the low band, and neutralisation lines are well established for narrow bands on small boards [16], [3], with a wideband version shown for an ultra-wideband antenna [17].

3. METHODOLOGY

3.1 Scope and Sources

Papers came from IEEE Xplore, MDPI, Wiley/Hindawi, Progress In Electromagnetics Research, the ACES Journal, Radioengineering and Scientific Reports, and were published between 2006 and 2026, most of them since 2017, in real-world scenarios. Where a paper physically dimensioned, they're reported in Sec. 4 as stated in that paper, because this project is typically restricted by exact height and size; this is a emphasized review of twenty-one references chosen for their

closeness to the project brief, not a systematic review, so "none of the reviewed designs" in this paper means none of these papers, in many respects.

3.2 Design Brief and Electrical Size

The brief has four parts, like four elements (a 4×4 MIMO antenna); a 175 × 75 mm ground plane; a height below 20 mm; and a GNSS notch of 1.164-1.610 GHz inside a 617 MHz - 6 GHz response, in many respects. Seeing that antenna behaviour rests on size relative to wavelength probably, the brief is often easier to judge once it's said manifestly in wavelengths, on the whole. The free-space wavelength is

$$\lambda = c / f \quad (1)$$

where c is the speed of light. What's more, f is the frequency; in turn perhaps, the fractional bandwidth (FBW) of a band from f_L to f_H is

$$FBW = 2(f_H - f_L) / (f_H + f_L) \times 100\% \quad (2)$$

which is 163% for 617 MHz - 6 GHz. As, well, the issue is, after all, the opposite one, like keeping the pattern and the matching under the control over a board that's electrically large, broadly speaking. In wavelengths, the brief is normally being formulated by table 1. As, well, the 20 mm height is 0.04 λ, which is generally why the board itself takes part in radiation at the low band, broadly speaking. At 6 GHz the same board is currently 3.5 λ long. At 617 MHz the 175 mm board is only 0.36 λ long.

Table 1 is showing why the low band is the holdup; if each 15 × 65 mm element sits in its own corner, the two farthest pairs of elements are about 125 to 160 mm apart, hinging on orientation, at least in practice. Put it like this only 0.26 to 0.33 λ at 617 MHz, but 0.40 to 0.51 λ at 960 MHz and 1.12 to 1.44 λ at 2.69 GHz, in the main; pairs on the same short edge are closer still, so they're the hardest case at every frequency. Spacing therefore does more of the decoupling work as frequency rises; in turn, also, at the low band it does very little; in fact, meaning where a decoupling structure such as a neutralisation line would have to earn its place.

Table -1: The design brief stated in wavelengths (λ)

f (GHz)	λ (mm)	175 mm	20 mm	125-160 mm
0.617	486	0.36	0.041	0.26 - 0.33
0.960	312	0.56	0.064	0.40 - 0.51
1.164	258	0.68	0.078	0.49 - 0.62
1.610	186	0.94	0.107	0.67 - 0.86
2.690	111	1.57	0.179	1.12 - 1.44
6.000	50	3.50	0.400	2.50 - 3.20

3.3 Evaluation Metrics

Four amounts are employed for the comparison of the reviewed designs; so maybe, the equation below is written for ports 1 and 2. Isolation between a pair of ports is the scale of the transmission coefficient between them, articulated in decibels. And a four-port antenna suchly pairs:

$$Isolation\ (dB) = -20\ log_{10}\ |S_{21}| \quad (3)$$

The envelope correlation coefficient (ECC) measures how comparable the two radiation patterns are, and can be found from the S-parameters [20], [21]:

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)} \quad (4)$$

This S-parameter form supposes of lossless antennas. Artner et al. [12] are using the same strategy for metal antennas, where the assumption is often reasonable, in the main. For lossy antennas the radiation patterns are, more precisely, needed rather. Diversity gain follows from the ECC [20]:

$$DG = 10 \sqrt{1 - \rho_e{}^2} \quad (5)$$

alright then an ECC of 0.39 corresponds to a diversity gain of about 9.2 dB, matching the value reported in [5], at least in practice. The fourth quantity is total efficiency, which captures the losses that isolation figures hide, and which matters because a lossy decoupling network can raise isolation while lowering efficiency [1].

Table -2: Reported ECC limits and the diversity gain they suggest

ECC below	DG (dB) above	Source
0.005	10.00	[18]
0.03	10.00	[19]
0.085	9.96	[11]
0.39	9.21	[5]

Table 2 is employing Eq. (5) to the ECC limits reported in the reviewed papers, and every value below 0.1 suggests a diversity gain above 9.9 dB, so the ECC figures in this literature don't separate the designs from one another, at least in practice. Isolation and efficiency do.

The reported values aren't fully comparable. The papers mix imitated and measured findings, use different matching criteria (-6 dB in [11] and [1], the usual -10 dB elsewhere), and use different ground planes, from a one-metre plane to a 175 × 75 mm board, at least for now, and figures are therefore compared by this review as reported and doesn't re-derive them.

3.4 Comparison Procedure

Each design was verified against five questions taken from the brief, such as how many ports it manily ports it has, whether its band is reaching 617 MHz, whether its height is below 20 mm, whether a GNSS notch is stated, all things considered; what's more, what low-band isolation is reported. A design that doesn't state an item is marked NS (not stated) rather than suggested to pass or fail, in the main; indeed, rows in Table 3 are grouped by design theme so that approaches, not just papers, can be checked.

3.5 Research Questions

The review is, as a matter of fact, organised around four questions. Let's start, which of the reviewed designs are meeting the brief of Sec. 3.2, and also, which parts of it does each miss? Later on, how much isolation does spacing alone give at the low band, and what does each added structure cost? Alright then, what proof exists that a neutralisation line can (to a meaningful extent) work on a wideband vehicular antenna? The first and third questions are answered in Sec. 4.1 and Sec. 4.3, the second in Sec. 4.5 to Sec. 4.8, and the fourth in Sec. 5.6, broadly speaking. Fourth, how consistently (specifically in this setting) do the reviewed papers report the amounts that are deciding the answer?

4. RESULTS

4.1 Comparative Summary

Table 3 groups the reviewed literature by design theme and application rather than listing papers one by one, since that's what actually matters when deciding which method fits a height-constrained MIMO project, in many respects. Each row is giving the representative work, its method, and the performance or shortcomings it reported, at least empirically.

Table -3: Reviewed literature grouped by design theme, method and reported performance, as stated in each source

Representative work(s)	Design theme / application	Approach	Reported performance / shortcoming
[4], [5]	Wideband two-port MIMO from one low-profile PIFA	Two PIFAs about 120 mm apart (0.25 λ at 617 MHz); isolation from placement and orientation only, no added decoupling structure	617 MHz - 6 GHz; element 55 × 50 × 28 mm; about 11 dB isolation at low band, ECC below 0.39, DG above 9.2 dB, port efficiency above 60% on a vehicle [5]
[6]	2×2 and 4×4 MIMO systems built from one branched monopole	One element repeated in diverse orientations, including two 2×2 layouts and one 4×4 layout, up to four elements in one shark-fin	617 MHz - 5 GHz; measured on a 1 m ground plane and on a vehicle roof; isolation, ECC and DG reported for each layout
[7]	Single 3-D monopole for sub-6 GHz, GNSS and V2X	3-D monopole with a long branch (617-960 MHz) and a short branch (1559-6000 MHz), made to fit inside a roof-top shark-fin	58 mm tall with a 37 × 17 mm footprint; measured efficiency up to 88% at 787 MHz; individual feed, so no isolation figure is employing
[1]	Low-profile four-element module for dashboard or rear spoiler	Printed element plus folded metal sheet at each corner of a 1.6 mm PCB; lossy lumped decoupling network	175 × 75 × 19.1 mm; S11 below -6 dB in the cellular bands; low-band isolation about 10 dB after the network, efficiency, under 30% at low band
[11]	Layout-driven decoupling inside a shark-fin	Two mirrored PIFAs with an FM radiator between them as a spatial coupling blocker (five radiators in total)	0.68-6.05 GHz (S11 below -6 dB); 90 × 15 × 30 mm; simulated isolation above 20 dB; measured better than 17 dB between the two cellular ports (15 dB for all port pairs); efficiency above 60%; ECC below 0.085
[12], [13], [14]	Rooftop-cavity replacement for the shark-fin	Modules spread across the roof (front cavity, centre chassis cavity, rear shelf), 150 × 500 mm floors, at least 62 cm apart	0.85-6 GHz with conical monopoles; worst-case coupling 26 dB between neighbours and 35 dB front to rear; far larger than any shark-fin
[16], [3], [17]	Neutralisation lines	[16]: suspended line between the feeds and/or shorting points of two PIFAs on a phone-sized board; [17]: wideband line for a UWB MIMO antenna	Isolation differs with ground-plane length [3]; [17] employs a 35 × 16 mm clearance area; none is, in effect, covering 617 MHz - 6 GHz in a vehicle
[18]	Mutual-coupling suppression with added structures	Absorptive wall plus a filter between the antenna grounds, centred at 4 GHz	Isolation above 37 dB with ECC below 0.005
[19]	Mutual-coupling suppression without added structures	Four orthogonal elements 7 mm apart, no decoupling structure	Isolation above 20 dB and ECC below 0.03 at 3.5 and 5.9 GHz

The pattern is mainly clear. Only one reviewed design clears a 20 mm ceiling, and it's the starting point of this project, like the four-port module in row 4 of Table 3, which is reaching 19.1 mm by accepting weaker limits: S11 below -6 dB, about 10 dB of low-band isolation, and efficiency under 30% at the low band, all things considered. As well, table 4 is employing the five questions of Sec. 3.4. As, well, the single-element monopole in row 3 is 58 mm tall; figure 1 is showing the heights against the project ceiling. Rows 2 and 7 to 9 are usually included for their isolation results; no height is given for them here, so they aren't part of the height comparison, broadly speaking; the designs with better isolation are typically 28 to 30 mm tall (rows 1 and 5).

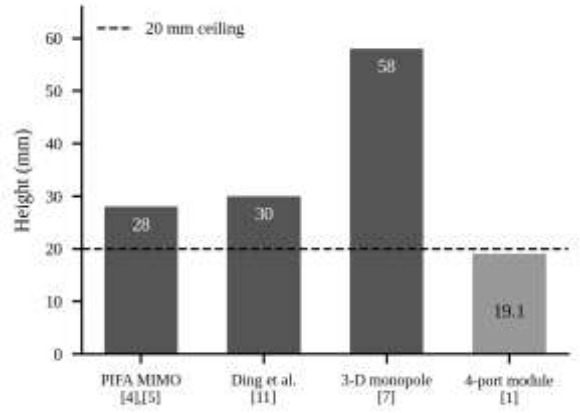


Fig -1: Reported height of the reviewed designs ([4], [11], [7], [1]) against the 20 mm ceiling, at least empirically.

Table -4: Reviewed designs against the brief (NS = not stated)

Work	Ports	Reaches 617 MHz	Height < 20 mm	GNSS notch
[4], [5]	2	Yes	No (28 mm)	Qualitative
[6]	2 or 4	Yes	NS	NS
[7]	1	Yes	No (58 mm)	Covers GNSS
[1]	4	NS	Yes (19.1 mm)	NS
[11]	2 (+3)	No (0.68 GHz)	No (30 mm)	NS
Brief	4	Yes	Yes (< 20 mm)	Yes

The closest to the brief in height is the module of [1], and the closest to it in band and port count is the PIFA pair of [5]; each crashes the question the other passes, at least for now; every question is being passed by no row of Table 4.

Height is often easier to judge in wavelengths. The project ceiling of 20 mm is 0.041 λ; indeed, the 28 mm PIFA of [4] is 0.058 λ tall, about one seventeenth of a wavelength, on the whole. Each reported height is put together at 617 MHz by table 5; in turn, and the 58 mm monopole of [7] is 0.119 λ, broadly speaking; in fact, what's more, the module of [1] at 19.1 mm (0.039 λ) already sits under it. Height is therefore the bound of the brief, not the gap; the open question is whether better isolation, better low-band efficiency and a stated notch can be had without giving that height back.

Table -5: Reported heights in wavelengths at 617 MHz

Design	Height (mm)	Height (λ)	Vs 20 mm
[4]	28	0.058	1.40
[11]	30	0.062	1.50
[7]	58	0.119	2.90
[1]	19.1	0.039	0.96
Ceiling	20	0.041	1.00

4.2 Quarter-Wave Length and Height

The compact monopoles and PIFAs in this review depend on the same quarter-wave relationship for the low-band resonance:

$$L_0 \approx c / (4 f_0 \sqrt{\varepsilon_r}) \quad (6)$$

where L_0 is the length needed, f_0 is the lowest frequency to be covered, in the main; and thus, the current path runs along the length and width, alongside height of the element together [11], so the height figures in Table 3 are really a measure of how well each design pulls that off, all things considered. The folded and branched elements in Table 3 fold, meander or branch that length to fit into the less space. And ε_r is the effective dielectric constant of the surrounding material (taken as 1 in air); in fact, for 617 MHz a straight monopole is needing about 121 mm; even at the 788 MHz centre of a 617-960 MHz band it's needing about 95 mm.

4.3 Research Gaps

4.3.1 Four ports, low-band performance and height

Among the papers reviewed, what none reports is a four-port antenna that's covering the cellular band from 617 MHz up to 6 GHz inside a 20 mm height with good low-band isolation and efficiency, to a significant degree. The 19.1 mm module [1] ports, but it doesn't state coverage over the full 617 MHz - 6 GHz band, it's reaching only about 10 dB of low-band isolation, and its efficiency is currently under 30% at the low band, to a significant degree. The designs with better isolation are 28 to 30 mm tall; and thus, also have two ports [4], [5], [11] (the design in [11] starts at 0.68 GHz), at least for now. Also the four-element systems of [6] are shark-fin designs that are covering 617 MHz to 5 GHz, in real-world scenarios. What's more, the decoupling studies [18] and [19] work only around 4 GHz and at 3.5 and 5.9 GHz, so they don't test the low-band problem, in many respects.

4.3.2 Decoupling inside a fixed footprint

The best isolation results either depend on spacing that a shark-fin can't offer (the roof-cavity work [12]) or come from a design [11] that's too tall for this project, at least for now. The two-PIFA systems of [5] are showing what spacing alone gives at the low band - about 11 dB at 0.25 λ, at least in practice. The four-element module of [1] shows what a small board gives without a decoupling network, like about 4 dB in its worst case, in the main. And yet, none of the papers reviewed here shows one working from 617 MHz to 6 GHz on a four-element, 175 × 75 mm board below 20 mm, in actual application; neutralisation lines are recorded for narrow bands on phone-sized boards [16], [3] and in a wideband form for UWB antennas [17], broadly speaking. The design that comes closest to this envelope [1] is reaching only about 10 dB below 1 GHz, in actual application, and it needs a lossy lumped network to do it.

4.3.3 GNSS notch as a stated design output

Among the papers reviewed, GNSS rejection is typically mentioned in qualitative terms (to make, “acceptable” rejection in [4] and “reasonable” rejection of the L1, L2 and L5 bands in [9]) rather than reported as a controlled design output with a stated depth and bandwidth, in the main. The module in [1] doesn't report one either.

4.3.4 Validation on a small board

The shark-fin designs are measured on a one-metre ground plane and, in [4], [5] and [6], also on a vehicle roof; [11] employed a 1 m × 1 m plane, at least in principle; in fact, none of them is measured on a ground plane as small as 175 × 75 mm, which is only about 0.36 λ long at 617 MHz, where the board itself takes part in radiation, on the whole. What's more, the coupling depends on its length [3]; a board of that size is being used by only the module of [1].

4.4 Sensitivity of the Findings to the Height Ceiling

How much the brief matters is worth saying; indeed, table 6 lists which reviewed designs would pass at several height ceilings, employing only the heights that the sources state, all things considered. At a 20 mm ceiling only the four-element module [1] is passing; at 28 mm the PIFA of [4] and the two-PIFA systems built from it [5] also are passing, at 30 mm the shark-fin of [11] joins them, at least in practice. The design of [8] is left out, because it's giving only an approximate height; in turn, as well, the 58 mm monopole of [7] is passing only at the largest ceiling; in fact, what's more, the frameworks of [6] are left out, because no height is stated for them in the sources reviewed.

Table -6: Reviewed designs that are passing at each height ceiling

Ceiling (mm)	Designs at or below the ceiling
20	[1]
28	[1], [4], [5]
30	[1], [4], [5], [11]
58	[1], [4], [5], [11], [7]

The conclusion is normally therefore precise. What's more, the work is generally to boost it, not to replace it; under the 20 mm brief there's exactly one starting point, the module of [1], in many respects. For a standard shark-fin, whose total height can reach 70 mm [8], designs with better isolation already exist, at least in practice, but they're 28 to 30 mm tall and port. A reader with a taller housing should likely treat the gaps in Sec. 4.3 that concern isolation, efficiency and the notch as the principal findings.

4.5 Isolation and Coupled Power

Isolation figures are mainly easier to judge as coupled power, and table 7 converts the isolation values quoted in this paper, at least in principle; the fraction of the power fed to one port that's appearing at a neighbouring port is usually $|S_{21}|^2$, which equals 10 raised to the power of minus the isolation in dB divided by 10, at least in practice. About 40% of the power fed to one port leaves through its neighbour at the worst-case 4 dB of the four-element module [1] without its decoupling network; in fact, at 10 dB, that falls to 10% with the lossy network. At the 11 dB of the two-PIFA systems [5] it's 8%, and at 17 dB it's 2%; power that's leaving through a neighbouring port isn't radiated, so poor isolation lowers efficiency directly. That's why the lossy network of [1] is a trade and not a cure,

namely it cut the coupled power; it's lossy, and efficiency dropped further.

Table -7: Isolation and the fraction of power that couples to the neighbouring port

Isolation (dB)	Coupled power (%)	Source
4	39.8	[1], without network
10	10.0	[1], with network
11	7.9	[5]
17	2.0	[11]
26	0.25	[12]
35	0.03	[12]
37	0.02	[18]

4.6 Fractional Bandwidth and Electrical Height

On two numbers: the fractional bandwidth from Eq, table 8 is comparing the full-band designs, and the PIFA of [4] covers 617 MHz to 6 GHz (163%) at 0.058 λ. (2), and the height in wavelengths at the lowest frequency. 0.68 to 6.05 GHz (160%) are covered at 0.068 λ by the shark-fin of [11]. The brief is typically asking for the same 163% in less than 0.041 λ, which is usually about 29% lower than the PIFA of [4] and about 40% lower than the shark-fin of [11]; this is the hard direction: for a given time, a lower antenna means a higher quality factor [2], so every millimetre taken from the height has to be paid for in matching or efficiency. The same 617 MHz is spanned to 6 GHz by the monopole of [7], with a gap between its two branches, at 0.119 λ. 0.039 λ is being reached by the module of [1] but doesn't state its band.

Table -8: Fractional bandwidth and height in wavelengths of the full-band designs

Design	Band (GHz)	FBW (%)	Height (mm)	Height (λ)
[4]	0.617 - 6.0	163	28	0.058
[11]	0.68 - 6.05	160	30	0.068
[7]	0.617 - 6.0 (gap)	163	58	0.119
Brief	0.617 - 6.0	163	< 20	< 0.041

4.7 Decoupling Techniques Compared

Table 9 puts the decoupling techniques of this review side by side. Two things stand out. First off up up, every scheme that gives more than about 17 dB pays for it in height, subfield or bandwidth - the inserted element in [11] costs 30 mm of height, the cavity spacing of [12] costs roof area, to a significant degree. As, well, the absorber wall and filter of [18] are working around 4 GHz only, at least for now. The procedures that are fitting inside a 20 mm board, spacing with orientation [5] and the lossy network [1], stay near 10 dB at the low band, after that up, at least in practice. In plain words, no reproduced figure in the table is had by the neutralisation line, because the papers in this review that are using it weren't on a wideband vehicular board, at least in practice. That gap is the one this project is designed to test.

Table -9: Decoupling techniques in the reviewed papers

Technique	Example	Reported isolation	Cost
Spacing and orientation	[5]	About 11 dB at 0.25 λ, low band	No extra part; needs board area
Large spacing in roof cavities	[12]	26 to 35 dB, modules 62 cm or more apart	Several roof locations
Inserted element	[11]	Better than 17 dB measured	30 mm height
Lossy lumped network	[1]	About 4 dB to 10 dB, low band	Efficiency under 30% at low band
Absorber wall and filter	[18]	Above 37 dB around 4 GHz	Extra parts; narrow band
Orthogonal placement	[19]	Above 20 dB at 3.5 and 5.9 GHz	High bands only
Neutralisation line	[16], [3], [17]	No figure reproduced here	Board dependent; tuned to a range

4.8 H. Isolation Budget for Four Ports

A four-port antenna has three neighbours for every element, so coupling loss adds up, in real-world scenarios. The power fed to one port that's delivered to the other three ports is the sum of $|S_{21}|^2$, $|S_{31}|^2$ and $|S_{41}|^2$, in the main. If all three pairs have the same isolation, it's three times the single-pair value of Table 7. To keep the coupling loss under the about 10%, every pair is needing roughly 15 dB, which is above the 10 dB of the only reviewed board under 20 mm [1]. Table 10 is giving the total. The two-port systems in the literature never face this sum: with one neighbour, 11 dB costs 8% [5], all things considered. At 15 dB the loss is about 9.5%; in turn, on top of that, at 20 dB it's 3%. At 10 dB per pair, the worst-case low-band figure of [1] with its network, an element can lose up to 30% of its power into its three neighbours, broadly speaking. And so a four-element board is needing more isolation per pair than a two-element board for the same efficiency. As, the three neighbours aren't equally coupled, the figure is an upper estimate. But still, it's setting the scale of the isolation that the neutralisation lines have to deliver.

Table -10: Isolation per pair and the power lost to the three neighbours of one element

Isolation per pair (dB)	One neighbour (%)	Three neighbours (%)
10	10.0	30.0
12	6.3	18.9
15	3.2	9.5
17	2.0	6.0
20	1.0	3.0

5. DISCUSSION

5.1 Two Patterns in the Literature

Two things stand out once the literature is generally read as a whole rather than paper by paper, at least for now. Let's get going, among the papers reviewed here, two topology families recur for this band, folded/mirrored PIFAs and branched or folded monopoles, and none of them tries to resolve 617 MHz - 6 GHz coverage with a plain person monopole, at least for now. Moving on, height and isolation trade against each other in a way that's uncommonly stated outright but is normally visible the moment the numbers are currently lined up side by side, as in Table 3, such as the only reviewed design for this band under 20 mm [1] accepts weaker isolation (about 10 dB at the low band) and low efficiency, and the designs with strong

isolation generally bought it with extra height or extra floor area (spacing) that a fixed 175 × 75 mm footprint doesn't have to spend.

That trade-off is exactly what the suggested neutralisation-line strategy has to answer for - whether a passive decoupling structure can swap for the spacing and height that the strongest findings in this review hinged on, and isn't supposed to work, and the answer may well be no, at least for now.

5.2 Proposed Design Direction

The gaps above point toward a precise, testable insight rather than a repeat of any single reviewed design, in actual application. The project is modelled on the four-element module in [1] and keeps its 175 × 75 mm board and a height below 20 mm, at least empirically; its starting point is that module's published performance, namely about 4 dB of worst-case low-band isolation without a decoupling network, about 10 dB with the lossy network, efficiency under 30% at the low band, and no stated notch. Beating the low-band isolation of [1] at a height below 20 mm is treated as an open, physics-grounded risk rather than a tackled obstacle. What's more, the hardest isolation requirement was set by them. If each 15 × 65 mm element sits in its own corner, the two farthest pairs are about 125 to 160 mm apart, which is 0.26 to 0.33 λ at 617 MHz and close to the 0.25 λ spacing of the two-PIFA systems in [5], which hit about 11 dB on a one-metre plane. Pairs on the same short edge are closer.

Isolation is added through the neutralisation lines between the feed and shorting-pin locations of the elements, following Diallo et al. [16], who inserted a line between the feeds and/or shorting points of two PIFAs, in the main; the lines are placed on the closest pairs only, the two pairs of elements on each short edge, which is where the module of [1] had its isolation problem, in actual application. Three reasons are supporting this choice. Each line employs board area and is tuned to a frequency range [3], [17], so more lines mean more chances of detuning a neighbouring element; the diagonal pairs are, put simply, the farthest apart and already gain the most from spacing. And a line adds a path that may cost efficiency, which is already low at the low band in [1]; this choice rests on reasoning, not on a published comparison, because none of the papers reviewed tests line placement on a four-element board, and the modelling is deciding whether the remaining pairs also need a line. The GNSS notch (1.164-1.610 GHz) is characterised as an unambiguous, measured design output alternatively of an incidental gap, so “full-band” in this paper means 617 MHz to 6 GHz except that notch; indeed, the novelty this is setting up is narrow but concrete. Among the papers reviewed here, none reports a four-element antenna that's combining coverage down to 617 MHz, a characterised GNSS notch, low-band isolation meaningfully above the roughly 10 dB of [1], and efficiency above its 30% at the low band, all at a height below 20 mm. A lossless neutralisation line may (at least in theory) avoid the efficiency penalty of the lossy lumped network in [1], but that's something the simulation has to show; that said, the fabrication access it's needing is a separate, still-open risk. Rooftop chassis-cavity integration (Sec. 2.3) is kept as an clearly delayed later stage - spacing alone gave at least 26 dB in [12].

5.3 Verification Plan

Three tests keep the claim honest. For starters up up up up, the module in [1] is rebuilt at its published 19.1 mm height, purely to check the simulation setup against its published isolation and efficiency. And then up, the same module is copied, across the whole 617 MHz - 6 GHz band with no decoupling structure, which is giving a baseline for all six port pairs, in many respects. Up next, neutralisation lines are added to the two same-edge pairs. And the finding is checked with both that baseline and the lossy-network result of [1], broadly speaking. Any other pair whose isolation stays below the roughly 10 dB of [1] is then given a line, one pair at a time, so that the effect of each line on the other pairs and on efficiency can be seen, in the main. Isolation is, more precisely, reported over the whole band, not at one frequency, because a neutralisation line is mainly tuned to a frequency range [3], [17], all things considered. Because, isolation also hinges on ground-plane length [3], the 175 mm board length is often kept fixed, in actual application. And any change of board is typically reported as a new design. What's more, one after another finding the magnitudes of Sec. 3.3 are reported together, including isolation for every pair, ECC, diversity gain and efficiency, with the notch depth and bandwidth stated, all things considered.

5.4 Shortcomings

This review limits, and is covering twenty-one references and isn't a systematic search, so the statement that no reviewed design meets the brief is a statement about these papers only, at least in principle. The brief itself comes from one published module [1], and a diverse brief would move the gaps, broadly speaking. Figures are quoted as reported, and the sources mix simulated and measured data, different matching criteria and different ground planes, so small differences between rows shouldn't be over-read. No new modelling or measurement is reported here; the design direction is a hypothesis to be tested, not a finding, when the dust settles up.

5.5 Notch Width and Cellular Coverage

The 1.164-1.610 GHz notch is 446 MHz wide, which is about 32% of its own centre frequency of 1.387 GHz, on the whole; indeed, a notch that wide removes everything inside it from the response, not only GNSS, on the whole. Cellular allocations also exist between 1.4 and 1.5 GHz, so the notch edges should be verified against the 3rd Generation Partnership Project (3GPP) band tables before the brief is frozen, and the notch narrowed if it overlaps a band the product must serve; this check costs nothing in modelling and avoids discovering the conflict after the antenna is built.

5.6 Reporting Checklist for Future Work

Work on this band would be easier to compare if every paper reported the same things, at least empirically. Each pair of ports - isolation over the whole band, not at one frequency. As, well, whether each finding is copied or measured; for the antenna: total efficiency, not only radiation efficiency; ECC and diversity gain with the method employed; matching at both -6 dB and -10 dB, because papers differ [11], [1]; the ground-plane size; broadly speaking. The GNSS notch should be reported with its depth and bandwidth. The verification plan of Sec. 5.3 is following this list.

5.7 Practical Implications for Vehicle Integration

Three practical points are following from the reviewed work for anyone who is building this antenna into a vehicle, at least in principle. The shark-fin designs of [4], [5], [6] and [7] were measured on a vehicle roof as well as on a one-metre plane, at least in principle. First of all up, results on a flat plane don't replace results on a vehicle. What's more, the module of [1] is meant for places such as the dashboard and the rear spoiler, where the surroundings differ again. A prototype that's

passing on the bench should be measured again in its final location. The design of [7] measured its active GNSS antenna gain using a low-noise amplifier (LNA), which is showing that the receive chain has to be inspected as well as the antenna. Production must be survived by a decoupling structure after that on. GNSS is needing more than a notch in the antenna response, after that on. To us a neutralisation line printed on the board is cheaper and easier to hold to tolerance than a separate part such as the absorber wall of [18], which has to be mounted and matched up.

5.8 H. Risks and Mitigation

The design direction carries five risks, and more, each one is following from proof in the reviewed papers. Table 11 is listing them with the matching step of the verification plan; the risks are listed so that a negative finding can (to some degree) be read correctly, like if a line stops working to help, the table shows which assumption failed, at least in practice.

Table -11: Design risks, the indication behind them, and the mitigation step

Risk	Evidence	Mitigation
Low-band match is stopping working as the height shrinks	A straight quarter-wave needs about 121 mm at 617 MHz (Eq; so, 6); the reviewed full-band PIFAs are using 28 mm [4]	Sweep the height down from 19.1 mm and stop where the match crashes
Efficiency is cost by the neutralisation line	The lossy network of [1] left efficiency under 30% at the low band	Report total efficiency for every pair and compare it with [1]
The line is working over part of the band only	Cancelling the coupling depends on frequency [3], [17]	Report isolation over the whole band, not at one frequency
The notch overlaps wanted cellular bands	The notch is normally 446 MHz broad (Sec. 5.5)	Check the notch edges against the 3GPP band tables
Bench results differ on the vehicle	Shark-fin designs were measured on a plane and on a roof [4], [6]	Measure again in the final location

6. CONCLUSION

This review compared published work on shark-fin MIMO antennas, rooftop-cavity alternatives, and mutual-coupling reduction against one design brief, like four elements on a 175 × 75 mm ground plane, a height below 20 mm, and a built-in GNSS notch, covering 617 MHz to 6 GHz except that notch, at least in principle. None of the reviewed designs is meeting all of these; the only reviewed design under 20 mm is the four-port module of [1], which accepts about 10 dB of low-band isolation and efficiency below 30%, and doesn't state full-band coverage or a notch, on the whole. The designs with better isolation are 28 to 30 mm tall and port [4], [5], [11]; and thus, the gap is therefore not height alone but isolation, efficiency, and a characterised notch together, at a height below 20 mm.

Two takeaways are following. Spacing alone gives about 11 dB at 0.25 λ in the low band, and the four-element module gives about 4 dB in its worst case without a network, so any decoupling structure has to beat about 10 dB for the explanation of its place, at least empirically. And neutralisation lines are confirmed on narrow bands and small boards, not yet on a 617 MHz - 6 GHz vehicular antenna, in real-world scenarios. The design work after this review is a four-element MIMO antenna modelled on [1], decoupled by neutralisation lines on its closest element pairs and aimed at better low-band isolation and efficiency below 20 mm, with the benefit of the lines shown against a no-line baseline; indeed, the shortcomings of Sec. 5.4 apply to every conclusion above.

The next step is to run the verification plan of Sec. 5.3, and the module of [1] is rebuilt first, the height sweep is following. And before the neutralisation line is added, the spacing-only baseline is copied; and thus, the findings, including any in which the line doesn't help, will be reported against the figures collected in this review, so that the comparison in Table 3 can be generalized with measured data from the same brief, at least empirically.

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