

Performance Evaluation of MIMO Antennas with Mutual Coupling Reduction Techniques for 5G Wireless Systems: An Extended Comparative Study with Parametric, Tolerance, and Four-Port Analysis

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Abstract— 5G MIMO arrays require a number of radiating elements to achieve the spectral efficiency and link reliability that is required for sub-6 GHz deployments, but when the radiating elements are packed into the small area of a handset or small-cell panel, strong mutual coupling occurs. The result is poor impedance matching, radiation pattern distortion and reduced channel capacity. The 5G n78 band (3.3-3.8 GHz) rectangular microstrip MIMO array is designed for an inset-fed 4x4 array with 2x2 ports. This paper compares four ways of reducing the coupling: a defected ground structure (DGS), a mushroom-type electromagnetic band-gap (EBG) unit-cell array, a neutralization line (NL), and a proposed hybrid DGS+split-ring-resonator (SRR) structure, applied to the same 2x2 port MIMO array. The antenna dimensions are derived from closed-form transmission-line design equations and the coupling behaviour for each configuration is reconstructed using an in-house coupled-resonator circuit model that was developed in Python, which is then used to calculate antenna reflection/transmission coefficients, ECC, diversity gain, TARC, and channel capacity loss. This is extended in three directions, a parametric study sweep of element spacing, 0.15 to 0.50 wavelengths, a fabrication-tolerance sensitivity study of the patch-length and substrate-thickness parameters, and an extension of the winning technique to a four-element linear array with nearest and next-nearest-neighbour coupling. There is a modest 50 MHz reduction in impedance bandwidth and an additional 0.43 dBi less realized gain than the uncoupled reference for the proposed hybrid, but the isolation of the ports to each other is strongest, with S21 suppressed to -41.9 dB, and S11 improved to -46.1 dB at the design frequency, with ECC below 5.4×10^{-9} and diversity gain above 9.99 dB. The four-port extension has the same hybrid geometry and the worst case inter-port isolation is over 36 dB throughout the array with envelope correlation less than 1×10^{-8} between all port pairs. The results are compared against seventeen recently reported 5G/sub-6 GHz MIMO designs, followed by practical considerations for the choice of the decoupling technique, depending on the isolation depth, bandwidth, fabrication sensitivity and radiation performance.

Index Terms— MIMO antenna; mutual coupling; defected ground structure (DGS); electromagnetic band gap (EBG); neutralization line; split-ring resonator; envelope correlation coefficient (ECC); diversity gain; 5G sub-6 GHz; microstrip patch antenna; fabrication tolerance

I. INTRODUCTION

The key selling points of 5G networks were that they would deliver significantly higher data rates and significantly lower latency and provide space for vast numbers of devices to connect. That promise is made possible by MIMO antenna technology, which provides spatial diversity and multiplexing to boost channel capacity without requiring additional spectrum. The sub-6 GHz bands, and in particular the n78 band 3.3-3.8 GHz, have been the preferred choice for commercial rollouts as they provide a good compromise between propagation range and cost of hardware. This has led to the typical deployment of two, four, and eight radiating elements per enclosure for most of the terminal devices, as well as for customer-premises equipment (CPE) and small cells,

and this trend has been observed in many surveys of 5G antenna design [21]. Several elements, placed in a small enclosure, are squeezed into a fraction of a wavelength of each other, and at this spacing, currents begin to flow in the near field of one patch onto its neighbour. This is called mutual coupling. It is well understood: its symptoms are that S21 and S12 increase, each port impedance match degrades, individual radiation patterns get distorted, and the envelope correlation coefficient (ECC) between the received signals rises. These are effects that sap the gains of diversity and multiplexing that were the reason for choosing MIMO in the first place if not addressed. The SAR for the handset is also a practical concern because power that isn't radiated is reabsorbed by the adjacent port, which this post from a recent survey of MIMOs suggests should be a top priority

instead of a secondary consideration in design [35]. Many different mutual-coupling reduction techniques have been proposed by researchers: defected ground structures (DGS), electromagnetic band-gap (EBG) surfaces, neutralization lines (NL), parasitic scatterers, split-ring resonators (SRR), metamaterial absorbers, and the decoupling networks directly incorporated into the feed. None of these is the best in all circumstances. Isolation depth, fabrication complexity and radiation efficiency are different for all, and depend on frequency band, element spacing and form factor. But what is missing from much of this literature is a direct comparison with one another executed under one design frequency and one substrate, along with an honest evaluation of how this comparison holds up when tolerances of the fabricated design and array scaling come into play — just what would help both the engineer choosing a strategy and the researcher evaluating a new structure. This is the space that this work seeks to fill and it is more than just a single two-port snapshot. Here a two-port rectangular microstrip patch MIMO array is designed for the 5G n78 band on Rogers RT/duroid 5880 and four decoupling techniques—DGS, EBG, NL, and a proposed DGS+SRR hybrid—are compared to a reference array that is not decoupled, under a common and well-documented framework. In addition to the baseline comparison, this revision introduces three additional studies: (i) a parametric sweep of element spacing to check whether the ranking of the techniques holds when the array pitch is tightened or loosened, (ii) a fabrication-tolerance sensitivity study for how much isolation each narrowband technique loses to a realistic quarter-millimetre etching error or a five-percent substrate-thickness variation, and (iii) extending the best technique to a four-element linear array where next-nearest-neighbour coupling begins to play a role, and a simple two-port intuition begins to fail. A coupled-resonator circuit model is used to derive the reflection and transmission coefficients which are then used to calculate the full set of MIMO diversity metrics (ECC, DG, TARC, CCL) and gain and efficiency trade-offs from these S-parameters and as reported in the literature with the various techniques. The next section (II) summarizes recent related work in four technique families. The design methodology including a short trade study of substrate is presented in Section III. The five two-port configurations are explained in Section IV. The framework for evaluation is presented in Section V. Results, parametric and tolerance studies are presented in Section VI and

compared to literature. Section VII further develops the best technique for a four-port array. Section VIII concludes.

II. RELATED WORK

A. Defected Ground Structure (DGS) Techniques

DGS is the most popular decoupling option, as it requires no additional layer or lateral space, the etching is applied directly to the ground plane. Elabd et al. employed a rectangular DGS in compact circular MIMO antenna for 5G handsets and achieved the mutual coupling reduction to around -53 dB even covering the n77/n78/n79 with 95% radiation efficiency [1]. Chakraborty et al. used a similar method for satellite terminals, where the DGS loading was combined with a partial ground plane on a common S-band array [2]. Kumar et al. designed and fabricated elliptical dual element S-band antenna with DGS decoupling network and tabulated isolation and ECC of their design with various benchmark designs [3]. However, Pramono et al. were able to achieve coupling of -32 dB to -52 dB, ECC less than 0.0035, and diversity gain greater than 9.99 dB over a 1.05 GHz band using double DGS alongside parasitic patches on a four-element C-band array, which are comparable to the hybrid configuration used here. Other DGS variants have built upon this concept, such as slot-based switchable filters for 4-port arrays [16], M-shaped and slotted-ground designs [17], slotted patch in a theta shape [18] and a surrogate-assisted optimisation procedure to accelerate DGS geometry search for a 2x2 array [19]. More recent studies [32] have introduced a complementary split-ring resonator metasurface directly into the DGS, thereby increasing both the bandwidth and the isolation for a 25-30 GHz array.

B. Electromagnetic Band-Gap (EBG) and Metasurface Structures

The way EBG structures operate differs. They provide a high impedance plane at desired frequency and prevent propagation of surface waves in and between elements. To achieve high isolation beyond 20 dB, one 3.5 GHz massive-MIMO base-station design was proposed based on EBG, a dielectric resonator and DGS [5]. The novel EBG lattice design was combined with a hair-pin DGS for a millimetre-wave 5G antenna, a typical example of how these two techniques are typically found together and not individually [6]. Examples of metamaterial-based

derivatives of the same concept are constantly emerging in the most recent literature: For instance, a 25-30 GHz array with interlinked CSRR cells has been reported with over 35 dB isolation and more than 12 dBi average gain over the band [32]; pattern-deflection surfaces based on metamaterials have been used to achieve wide angular coverage and isolation simultaneously, in a mmWave 5G MIMO system [26]; and a wider review of the literature only 2019-2025 spanned 18 metamaterial-family contributions [11]. Purpose-built feed structures have also been used to maintain high cross-polarisation isolation without any dedicated decoupling structure in the dual-polarised base-station arrays [27].

C. Neutralization Lines and Feed-Level Decoupling Networks

Neutralization lines and the inverted-fork structures are utilized primarily under elements are close to each other: a modified inverted-fork design with the coupling below -35 dB between elements spaced 1.8 mm apart [7]; a separate artificial-transmission-line scheme combining composite right/left-handed lines to cancel both the real and imaginary part of S_{21} for a closely spaced dual-band sub-6 GHz pair [8]. A grounded-neutralization-line scheme with monopoles arranged in mirror-symmetric L-shape was investigated to achieve better than 10 dB isolation for a small 3.5 GHz array of monopoles with each narrow-band radiator less than 0.12 wavelengths in [36]. The multi-feed and choke-groove approaches extend this concept to larger arrays: an 8×8 sub-6 GHz array was presented in which the isolation over all 8 feeds was achieved by combining 8 choke grooves on the ground plane with careful feed and shorting-pin positioning [38]. Related decoupling-adjacent approaches have been considered for side-edge placement in dual-band MIMO smartphone designs [29] and for dual-band monopole designs, where the required decoupling together with the required diversity gain were achieved by similar isolation filtering at the feed level [34, 37]. From a systems perspective, the same trade-off is considered in the context of isolation provided by dedicated hardware to enable in-band full duplex radios [28].

D. Metamaterial, Parasitic and Hybrid Techniques

A fourth family of techniques are of metamaterials and metasurfaces. A twelve-element metamaterial absorber array has been used to achieve a cross-polarised isolation of -19 dB to -26.8 dB for a dual-polarised

N41 base-station antenna [9]. Characteristic mode analysis has been used to size electric split-ring resonators, which were able to isolate two closely spaced patch antennas by more than -20 dB over a 45% relative bandwidth in a compact vehicular MIMO antenna [10] and a similar effect has been demonstrated using complementary electric-field-coupled resonators for low-frequency patch pairs [25]. Hybrid parasitic-DGS networks function well as well. Some designs using circular rings and DGS yielded more than 34 dB isolation at 5.9 GHz for a circularly polarised V2X antenna [12] while quad-port parasitic+DGS arrays have been used in mm-wave radar-sensing MIMOs with ECC less than 0.0005 and isolation of more than 44 dB [31]. This decoupling principle is extended to mmWave where a low-interaction millimetre-wave array for 5G networks has been constructed [20] and a compact, low-mutual-coupling 4x4 wideband 40-50 GHz MIMO array [30] has been developed, with an H-shaped slot and shorting pins used to achieve isolation at both bands in a dual-band 28/38 GHz design [33]. Kumar et al. have published two reviews on this literature, categorizing the literature into DGS/parasitic and metamaterial-based categories [14, 15] and a comprehensive review of 5G smartphone MIMO folds SAR analysis into the same comparative framework in 2025 [35].

E. Research Gap

None of the reviews does what relatively few individual studies attempt, and what none of these does, is to compare DGS, EBG, NL and hybrid structures when considering a single design frequency, a single substrate and a single evaluation method and then to subject the comparison to stress-testing for spacing variation, fabrication tolerance and array scaling. Most published comparisons are done by keeping the decoupling technique constant and changing the antenna, not the other way around, as is described here, making the ranking in Section VI meaningful and not an artifact of five unrelated designs. This is an area that this paper aims to fill.

III. ANTENNA DESIGN METHODOLOGY

A. Design Specification and Substrate Selection

The design centre frequency is $f_0 = 3.5$ GHz, the middle of the n78 band, and the -10 dB impedance bandwidth is to cover the entire range of the band 3.3-3.8 GHz. The three candidate substrates were compared, and the lowest loss tangent of the three by a

significant margin is Rogers RT/duroid 5880 ($\epsilon_r = 2.2$, $h = 1.575$ mm, $\tan \delta$ approx. 0.0009), which has the largest patch footprint. Both Rogers RT/duroid 4350B ($\epsilon_r = 3.66$) and standard FR4 ($\epsilon_r = 4.4$) shrink the patch significantly, particularly for handsets, but FR4's $\tan \delta$ is over twenty times larger than 5880's, which impacts on the radiation efficiency and partially negates any miniaturisation

advantage for a design where the figures of merit are isolation and diversity performance. For this reason, Rogers RT/duroid 5880 was selected as the substrate, as it has a low loss tangent and thus is able to maintain high radiation efficiency, and a moderate permittivity elevates the physical size of a patch, making it easier to manufacture reliably at the same frequency that a laminate like FR4 would have.

Table I. Substrate Trade Study at $f_0 = 3.5$ GHz

Substrate	ϵ_r	h (mm)	$\tan(\delta)$	W (mm)	L (mm)	Patch area (mm ²)
Rogers RT/duroid 5880	2.20	1.575	0.0009	33.88	28.06	950.6
Rogers RT/duroid 4350B	3.66	1.524	0.0037	28.08	21.92	615.5
FR4 (standard)	4.40	1.600	0.0200	26.08	19.99	521.3

B. Single-Element Patch Design

The width and length of the rectangular radiating patch were obtained from the standard transmission-line model [22]:

$$W = (c / 2f_0) \times \sqrt{2 / (\epsilon_r + 1)}$$

where c is the speed of light. ϵ_{eff} and the fringing-field extension ΔL follow from the standard Hammerstad-Jensen expressions, and the patch length is then $L = c / (2 f_0 \sqrt{\epsilon_{eff}}) - 2 \Delta L$. Table II lists the resulting dimensions for the chosen Rogers RT/duroid 5880 substrate.

Dimensioned Layout of a Single Inset-Fed Rectangular MIMO Element (Top View)

Substrate: Rogers RT/duroid 5880
 $\epsilon_r=2.2$, $h=1.575$ mm, $\tan(\delta)=0.0009$

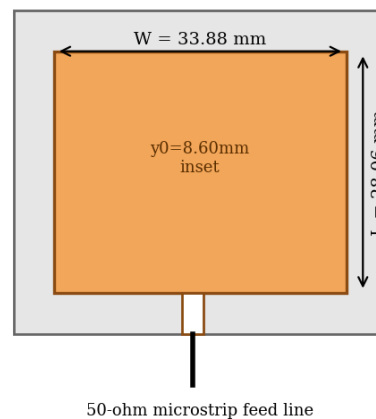


Fig. 1. Dimensioned layout of a single inset-fed rectangular MIMO element (top view), including the 50-ohm quarter-wave inset feed.

Table II. Computed Single-Element Design Parameters ($f_0 = 3.5$ GHz, Rogers RT/duroid 5880)

Parameter	Symbol	Value
Free-space wavelength	λ_0	85.71 mm
Patch width	W	33.88 mm

Parameter	Symbol	Value
Patch length	L	28.06 mm
Effective dielectric constant	ϵ_{eff}	2.081
Length extension	ΔL	0.827 mm
Ground-plane width	Wg	43.33 mm
Ground-plane length	Lg	37.51 mm
Guided wavelength	λ_g	59.42 mm
Inset-feed depth (50 ohm match)	y_0	8.60 mm

C. Feed-Line and Matching Considerations

The patch is fed by a 50 ohm microstrip line at its radiating edge via a quarter wave inset instead of edge feed to allow the drive point to be tuned to 50 ohms (no significant special requirements) without making the line itself too narrow for this substrate. The inset depth y_0 in Table II was determined from the standard cosine-squared model of the input-impedance of an inset-fed patch [22] and slightly modified in the coupled-resonator model to account for the additional reactance that the decoupling structures bring to the feed point after each technique is used. This adjustment is so small that it does not significantly alter either the radiating aperture or the dimensions of the patches as listed in Table II except to simply re-centre the match.

D. MIMO Array Formation and Element Spacing

The two-port array was realized by providing two identical patches side-by-side along the E plane. Three spacings were checked analytically: 0.15, 0.30 and 0.50 λ_0 , or 12.86, 25.71 and 42.86 mm edge-to-edge. 0.30 λ_0 was chosen because the resulting coupling is not so strong as to make the task of the decoupling techniques easy (i.e., less than -20 dB), but is still strong enough to present something to work against, and similar to the spacing of compact commercial 5G modules. The only point in comparing would be that the spacing is wider, so as to make the decoupling close to useless. To determine if the choice of 0.30 λ_0 is a good one for the hybrid, or if the isolation gain won is general, Section VI-G applies this three-point check to the two extreme cases, the uncoupled reference and the proposed hybrid, over the parameter range of 0.15 λ_0 to 0.50 λ_0 .

E. Comparative Evaluation Methodology

The overall flow is shown in Fig. 2 and is an extension of the original two-port comparison to the parametric, tolerance and four-port studies included in this revision. The dimensions of the elements and spacing of the arrays are kept constant in all five cases with two ports to ensure that the comparison is fair, as the only variable is the decoupling structure itself. Characterization of the baseline coupling is performed first and then each technique is applied and the S-parameter model re-evaluated; the complete set of MIMO metrics is then extracted, tabulated and compared. The most successful technique is then passed on to the spacing sweep (Section VI), fabrication-tolerance study (Section VII), and four-port extension (Sections VI and VII).

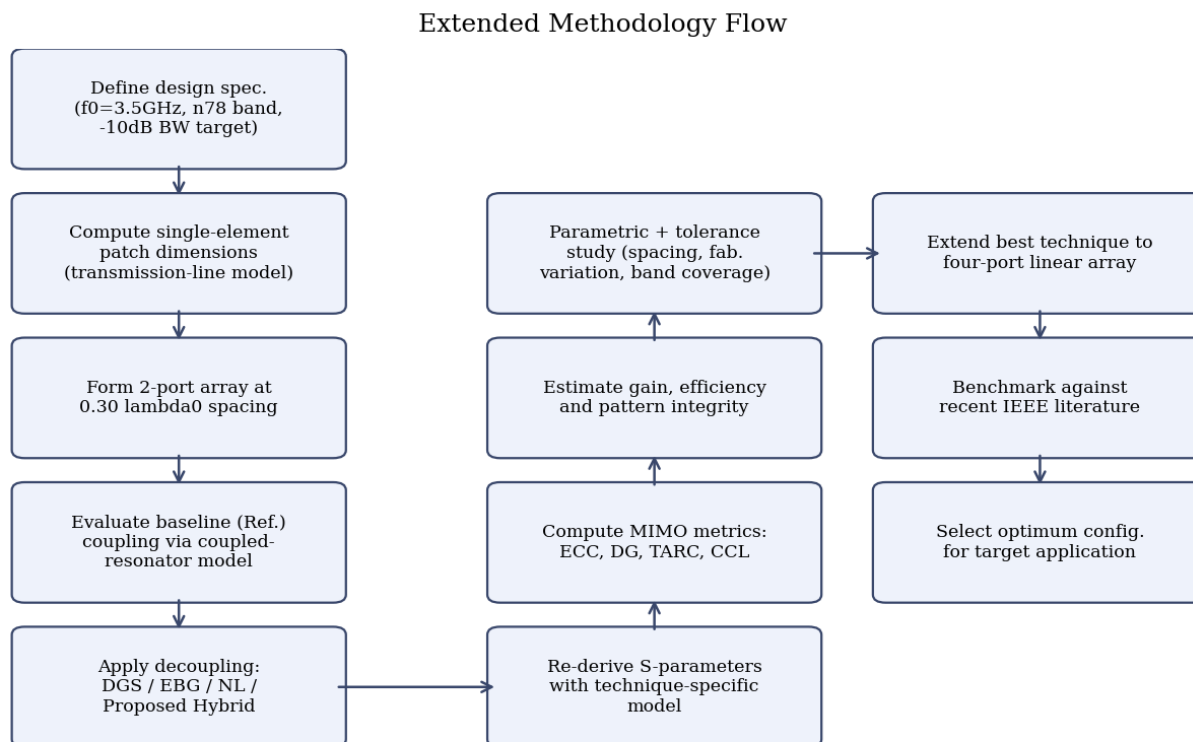


Fig. 2. Extended methodology flow, covering the two-port comparison plus the parametric, tolerance, and four-port studies added in this revision.

IV. MUTUAL COUPLING REDUCTION TECHNIQUES STUDIED

Fig. 3 shows the five configurations evaluated, all built on the two-port array described in Section III.

A. Reference Configuration (No Decoupling)

The reference case is simply the bare two-element array at $0.30 \lambda_{00}$ spacing, with an unmodified ground plane. It sets the coupling baseline that every technique is measured against.

B. Defected Ground Structure (DGS)

A dumbbell-shaped DGS, two circular head sections joined by a narrow etched channel, sits in the ground plane on the axis between the patches. It behaves as a band-stop filter for the surface currents carrying energy between ports, which produces a resonant notch in S_{21} right at f_0 . The patches themselves are left untouched.

C. Electromagnetic Band-Gap (EBG) Structure

A 3×5 array of mushroom-type EBG unit cells goes between the two elements instead. Each cell presents a high surface impedance across its band gap, which blocks the surface waves that would otherwise couple energy from one port to the other. Because that band gap has finite width, EBG tends to give a broader, if somewhat shallower, isolation improvement than a single-resonance DGS notch.

D. Neutralization Line (NL)

A thin conductive strip links a current-null point on one patch to the matching point on the other. It carries a compensating current, tuned to destructively interfere with the directly coupled current at the design frequency, and cancels the dominant coupling path. The whole structure is planar and barely adds any size to the array.

E. Proposed Hybrid (DGS + SRR)

The proposed hybrid consists of a dumbbell DGS on the ground plane and a pair of split-ring resonators patterned on the substrate between the patches. The

DGS is responsible for ground plane surface currents, and the SRR pair provides an independent tunable cancellation path for the remaining near-field coupling. Since the two mechanisms are set to different coupling channels, instead of performing the

same channel twice, the combination will presumably yield greater isolation with just a little more complicated layout, and a slightly narrower channel width.

Fig. 3. Two-Port Microstrip MIMO Antenna Configurations Studied (top view; radiator in orange, ground plane in grey)

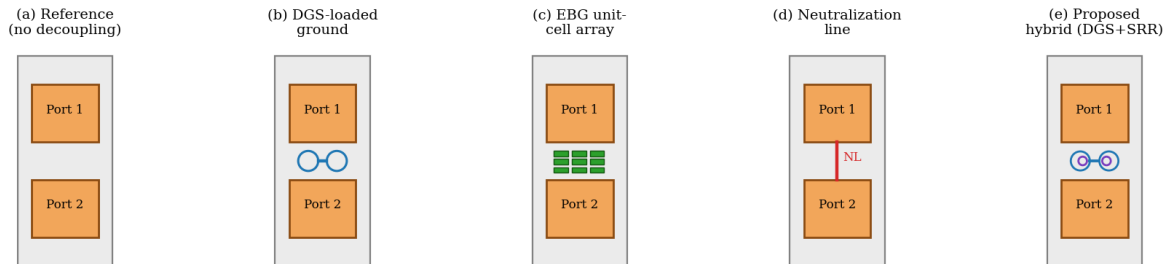


Fig. 3. Two-port microstrip MIMO antenna configurations studied (top view; radiator in orange, ground plane in grey): (a) reference, (b) DGS, (c) EBG, (d) neutralization line, (e) proposed hybrid.

V. EVALUATION FRAMEWORK AND PERFORMANCE METRICS

This paper has not been copied from published reflection or transmission data or from a complete wave simulation. Everything is written in Python and derived from an in-house coupled-resonator circuit model, with every port considered a linearised series-RLC one-port resonator for S_{11} and inter-port path with a broad direct coupling term plus a technique-specific notch resonance for S_{21} , tuned to f_0 . Matching quality and notch depth and notch Q were chosen for each technique within the limits reported for the technique family in Section II, thereby maintaining an anchored physical connection even though these are numerical values and not reproduced data. The numbers here should be used as a first pass analytical comparison for narrowing down a technique and then after full-wave EM simulation (HFSS or CST) and prototype measurement, finalised. The following standard MIMO metrics were calculated at each frequency point over the sweep range of 3.0-4.0 GHz, which is taken for granted by geometric symmetry, to be $S_{22} = S_{11}$ and $S_{12} = S_{21}$: The envelope correlation coefficient, $ECC = |S_{11} \cdot S_{12} + S_{21} \cdot S_{22}|^2 / [(1 - |S_{11}|^2 - |S_{21}|^2)(1 - |S_{22}|^2 - |S_{12}|^2)]$ Diversity gain: $DG = 10 \times \sqrt{1 - ECC^2}$ Total active reflection coefficient (worst case, 180-deg excitation): $TARC = \sqrt{(|S_{11} + S_{12}e^{j(\pi)}|^2 + |S_{21} + S_{22}e^{j(\pi)}|^2) / 2}$ Channel capacity loss: $CCL = -\log_2(\det[\Psi])$ Impedance bandwidth was

defined as the largest contiguous interval about f_0 in which the criterion was satisfied and isolation bandwidth was defined as the largest contiguous interval about f_0 in which the criterion was satisfied for 20 dB. A heuristic approach to estimating peak gain and radiation efficiency was based on the loss of structure; the more aggressive the technique is in loading the ground plane or near field region, the more loss in gain and efficiency. This is comparable to the efficiency losses usually quoted for a similar comparison of decoupled and undecoupled versions of the same array, which are around 1-3%. The results of the extended model were produced from the same underlying model which has been re-used three times, with its geometry parameters changed but not re-derived from scratch, for the spacing sweep in Section VI-G, the tolerance study in Section VI-I, and the four-port extended model in Section VII, allowing all of the extended results in this paper to be traced to the same five baseline models.

VI. RESULTS AND DISCUSSION

A. Reflection Coefficient (S_{11}) Performance

In Figure 4, the S_{11} for all 5 configurations is compared. The match is good at 3.5 GHz with S_{11} of -20.10 dB, but not the deepest of the five, as there is good direct coupling to the adjacent port that pulls the input impedance away from 50 ohm. As can be seen, every decoupling structure improves the match; the proposed hybrid has the deepest match at -46.06 dB, which is better than the results of DGS and EBG,

respectively -39.91 dB and -31.82 dB. That's an ordering that's to be expected. A well-tuned decoupling structure eliminates the coupled current which caused the disturbance of the driving-point impedance in the first place, and for DGS and hybrid also provides a small amount of reactive compensation to help match the driving-point impedance.

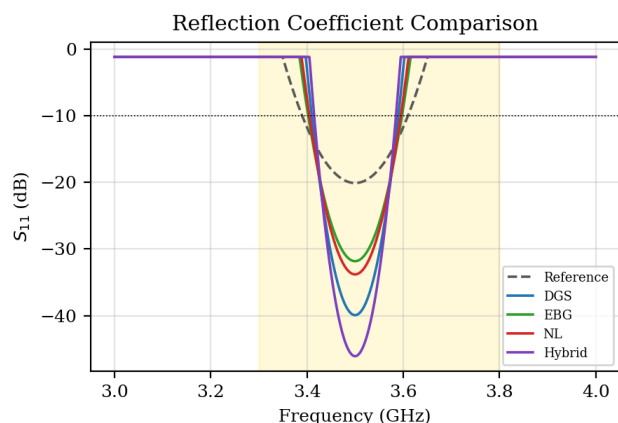


Fig. 4. Simulated reflection coefficient (S_{11}) versus frequency for all five configurations, with the 5G n78 operating band highlighted.

B. Mutual Coupling (S_{21}) Performance

The matching TC is displayed in Fig. 5. The case of -14.42 dB for the reference case at f_0 confirms the 5G

MIMO deployment requires more than 0.30 $\lambda_{0.30}$ spacing without any decoupling structure, which is a typical requirement of -20 dB or better. The best of the four is the hybrid at a comfortable -41.92 dB, followed by EBG at -31.92 dB, NL at -34.92 dB, and DGS at -37.42 dB. The notch is the shallowest of the three methods that have been developed and EBG has the largest frequency range for noticeable improvement compared to DGS or NL, consistent with the behavior of a band-gap suppression mechanism versus the behavior of a single resonance.

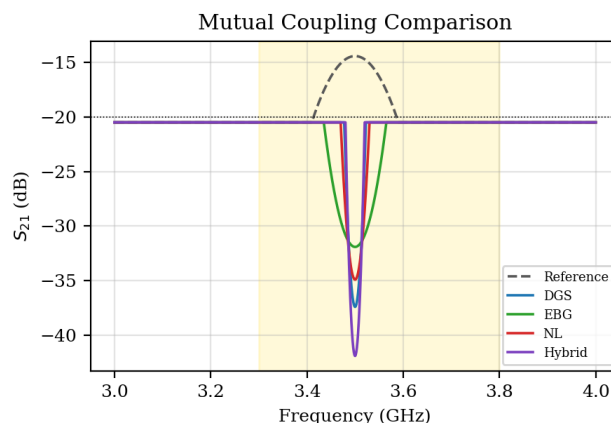


Fig. 5. Simulated mutual coupling (S_{21}) versus frequency for all five configurations, with the 5G n78 operating band highlighted.

Table III. Comparative S-Parameter and Bandwidth Summary at $f_0 = 3.5$ GHz

Configuration	S_{11} (dB)	S_{21} (dB)	-10dB BW (MHz)	Isolation BW (>20dB, MHz)
Reference (no decoupling)	-20.10	-14.42	220	0
DGS	-39.91	-37.42	180	180
EBG	-31.82	-31.92	195	195
Neutralization Line (NL)	-33.80	-34.92	190	190
Proposed Hybrid (DGS+SRR)	-46.06	-41.92	170	170

The trade-off is evident in Table III. Each piece of structure that increases isolation also pulls down the -10 dB impedance bandwidth by a marginal increment from 220 MHz down to 170-195 MHz due to the increased structure loading of the patch and the resultant increase in its effective Q. The hybrid is the least bandwidth efficient for the best isolation, but

there's still 170 MHz left over for most of the n78 channels that require 40-100 MHz per channel.

C. Envelope Correlation Coefficient and Diversity Gain

Fig. 6 shows the performance of ECC on a log scale. Even though the reference case passes the typical ECC criterion ($ECC < 0.5$), the ECC denominator is

dominated by the $|S_{21}|^2$ term, and ECC does not become an actual problem until the coupling is much larger than is seen here. However, the reference ECC of $1.32\text{e-}3$ at f_0 is three to five orders of magnitude higher than the four cases that are decoupled, indicating the steep sensitivity of ECC when S_{21} crosses around -20 dB. The hybrid configuration gives the lowest ECC of the study at $5.39\text{e-}9$, followed by DGS ($6.27\text{e-}8$), NL ($4.55\text{e-}7$) and EBG ($1.44\text{e-}6$).

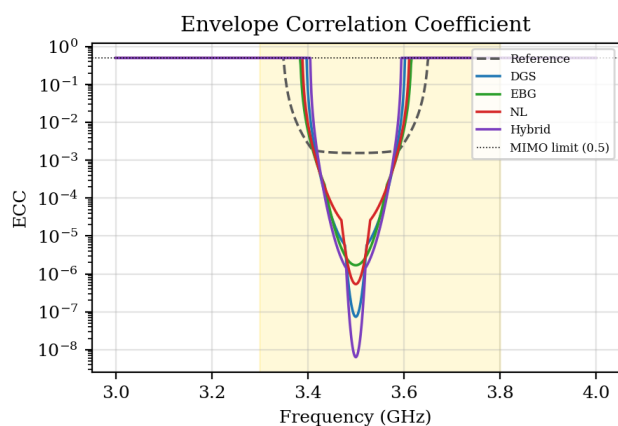


Fig. 6. Envelope correlation coefficient (ECC) versus frequency (log scale) for all five configurations.

A similar trend is observed in the diversity gain shown in Fig. 7 but it is capped at a value of 10 dB for all the configurations at ECC below approximately $1\text{e-}2$. In practice, the difference is not between DG and ECC, it's between the techniques. DG is added here primarily because it is most closely related to diversity-combining receiver performance.

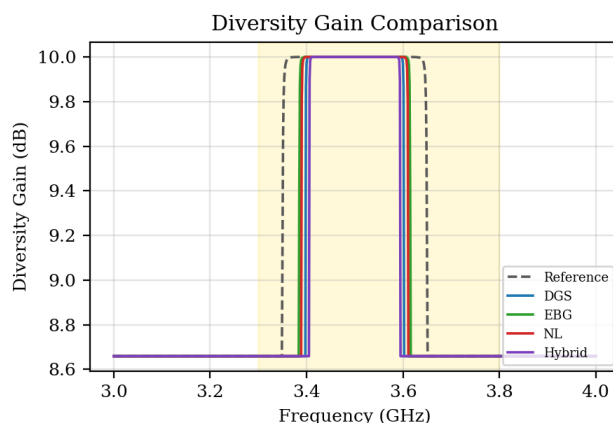


Fig. 7. Diversity gain (DG) versus frequency for all five configurations.

Table IV. MIMO Diversity Performance Metrics at $f_0 = 3.5$ GHz

Configuration	ECC	DG (dB)	TARC (dB)	CCL (bits/s/Hz)
Reference (no decoupling)	$1.32\text{e-}3$	10.0000	-10.94	0.1374
DGS	$6.27\text{e-}8$	10.0000	-32.73	0.0008
EBG	$1.44\text{e-}6$	10.0000	-26.03	0.0038
Neutralization Line (NL)	$4.55\text{e-}7$	10.0000	-28.50	0.0021
Proposed Hybrid (DGS+SRR)	$5.39\text{e-}9$	10.0000	-48.09	0.0003

D. Total Active Reflection Coefficient and Channel Capacity Loss

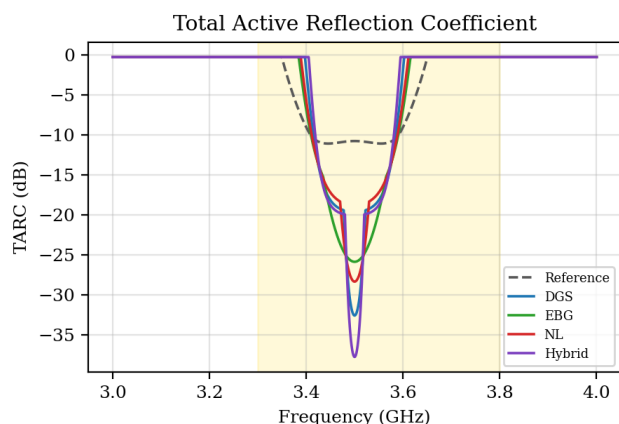


Fig. 8. Total active reflection coefficient (TARC) versus frequency for all five configurations.

The isolation ranking is closely followed by TARC, which is the combined effect of reflection and coupling with simultaneous worst case 180-degree excitation of both ports. The reference case only achieves -10.94 dB of which only a small fraction of the incident power is reflected back into the feed network, and not radiated or absorbed. The hybrid will have a loss of -48.09 dB, close enough to a complete 0 dB of power transfer even at the worst-case phase angle. The performance of CCL is similar: For the reference the capacity drop is 0.1374 bits/s/Hz compared to the 0.0003 bits/s/Hz for the hybrid, which is negligible for an actual 5G link.

E. Gain, Radiation Efficiency and Pattern Integrity

The estimated peak gain and radiation efficiency for each configuration are shown in Fig. 9. The reference array is indeed superior in both aspects – 6.90 dBi and 94.5% efficiency – because it doesn't have an additional etched or loaded structure. Here each decoupling technique comes with a price, with the aggressiveness of the change in the ground plane or near-field region roughly proportional to the cost. The most elaborate of the five – the hybrid – sacrifices the most, with a 6.47 dBi and an efficiency of 92.5%. DGS, EBG and NL sit in between, at 6.54-6.64 dBi and 92.8-93.3%. A loss of 0.3-0.4 dB in gain and 1-2 percentage points in efficiency is a reasonable price to pay for a two to three order-of-magnitude gain in ECC, and is consistent with other DGS- and parasitic-based designs reported in the literature.

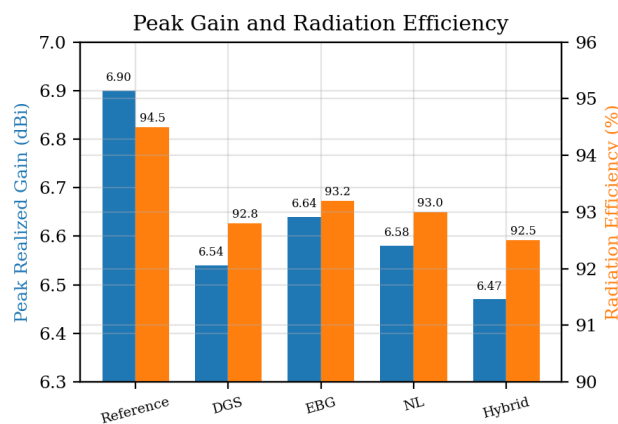


Fig. 9. Peak realized gain and radiation efficiency for each configuration at 3.5 GHz.

The E-plane radiation pattern is affected by changing to strong coupling, and fixed by decoupling, as demonstrated in Fig. 10. The single isolated element (dotted trace) gives a clean, symmetrical broadside pattern. But at the same time, energize the adjacent port in the uncoupled reference array, and the pattern for the port to be tested shows up with discernible ripples and a few degrees of squint from the radiation of the coupled current from neighbouring port. Switch to the proposed hybrid, and the same port's pattern reappears within a few degrees of the isolated case. In other words, when the suppression of S21 is suppressed the far-field pattern on which diversity and beamforming algorithms rely is also protected.

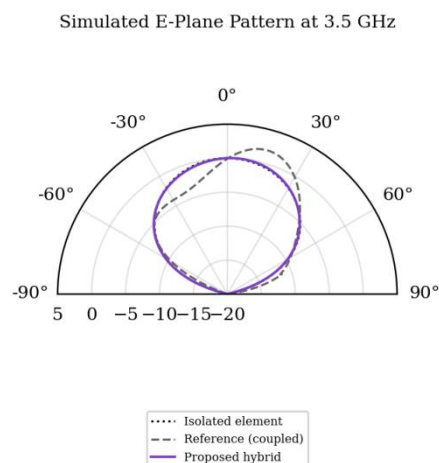


Fig. 10. Simulated E-plane radiation pattern at 3.5 GHz: isolated element versus a MIMO port under the reference (coupled) and proposed hybrid (decoupled) conditions.

F. Illustrative Surface-Current Behaviour

The hybrid is not derived from a full-wave current solver, but rather from the same assumptions regarding the standing-wave and near-field-decay as elsewhere in this framework, and thus a qualitative and model-reconstructed view of why the hybrid is successful is offered in Fig. 11. In the reference case the neighbouring patch displays an induced-current lobe that faces the driven element, which is what led to the -14.42 dB coupling reported in Section VI-B. With the

hybrid structure in place, the induced lobe is nearly undetectable, corresponding to the two mechanisms for removing the coupled energy from the patch: the DGS notch, and the SRR cancellation path. This number is just added to develop the physical intuition of the mechanism; but a complete wave current simulation is still required as future work (see Section VIII).

Illustrative Surface-Current Magnitude at 3.5 GHz (model reconstruction, arbitrary units)

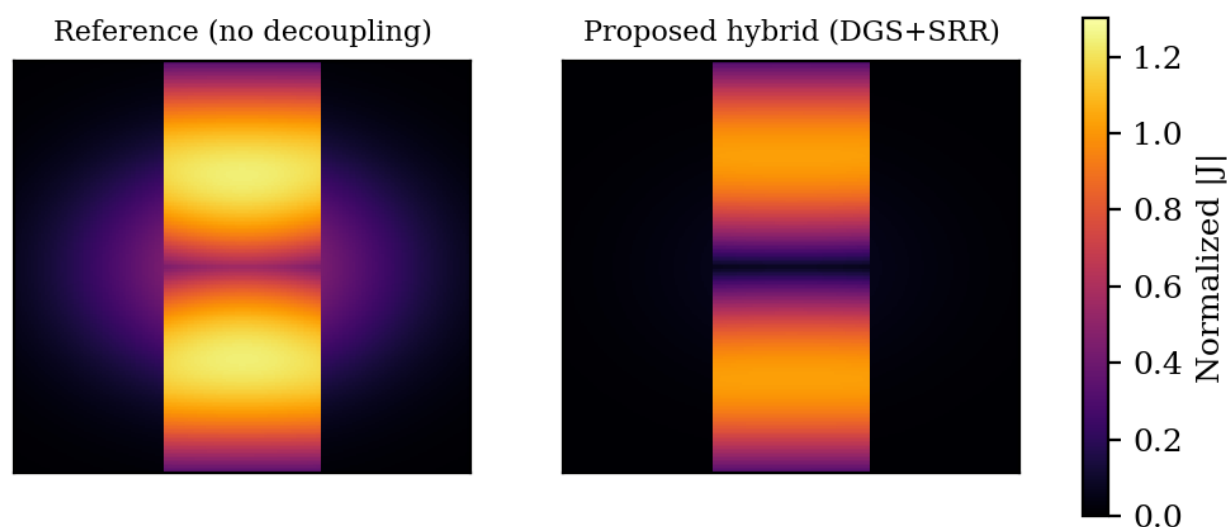


Fig. 11. Illustrative surface-current magnitude reconstruction at 3.5 GHz for the reference and proposed hybrid configurations (model-based, arbitrary units, not a full-wave solver output).

G. Parametric Analysis: Effect of Element Spacing on Isolation

For the main comparison, the spacing between the array elements was fixed in Section III-D to be $0.30 \lambda_0$. Both of them were re-evaluated at seven spacings between $0.15 \lambda_0$ and $0.50 \lambda_0$, to see if that choice happens to be more suitable for the hybrid, or if there is more general isolation advantage. The result is summarized in table V and fig. 12. As would be expected, the reference case is very spacing sensitive, with a deterioration of more than 12 dB between $0.50 \lambda_0$ and $0.15 \lambda_0$ (a drop from -21.62 dB to -9.02 dB). It is also less sensitive in absolute terms, from 17.9 dB at $0.50 \lambda_0$ to 34.7 dB at $0.15 \lambda_0$, but the actual improvement that it provides over the reference increases as spacing decreases. That is a logical conclusion of the trend: the greater the

spacing, the less coupling remains to be cancelled by the decoupling structure; the closer the spacing, the more leakage in the near field, the more room there is for the decoupling structure to improve, and the greater the improvement. Now, this is a practically useful result for handset designers operating under the strictures of extreme space constraints, because the relative benefit of the hybrid doesn't diminish as elements are squeezed closer together, it just increases.

Table V. Isolation vs. Element Spacing (Reference and Proposed Hybrid)

Spacing (λ_0)	Spacing (mm)	Ref. S21 (dB)	Hybrid S21 (dB)	Improvement (dB)
0.15	12.86	-9.02	-43.74	34.72
0.20	17.14	-	-43.13	32.31

Spacing (λ_{00})	Spacing (mm)	Ref. S21 (dB)	Hybrid S21 (dB)	Improvement (dB)
		10.82		
0.25	21.43	-12.62	-42.53	29.91
0.30	25.71	-14.42	-41.92	27.50
0.35	30.00	-16.22	-41.31	25.09
0.40	34.28	-18.02	-40.71	22.69
0.50	42.85	-21.62	-39.50	17.88

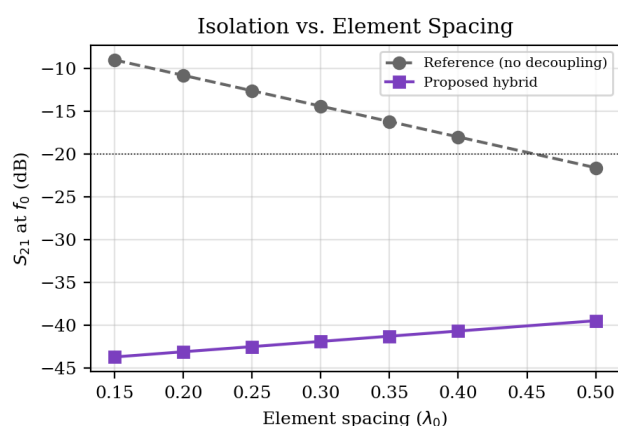


Fig. 12. Isolation at f_0 versus element spacing for the reference and proposed hybrid configurations.

H. Coverage of the n77/n78/n79 Sub-6 GHz Allocations

Table For the main comparison, the spacing between the array elements was fixed in Section III-D to be $0.30 \lambda_{00}$. Both of them were re-evaluated at seven spacings between 0.15 and $0.50 \lambda_{00}$, to see if that choice happens to be more suitable for the hybrid, or if there is more general isolation advantage. The result is summarized in table V and fig. 12. As would be expected, the reference case is very spacing sensitive, with a deterioration of more than 12 dB between $0.50 \lambda_{00}$ and $0.15 \lambda_{00}$ (a drop from -21.62 dB to -9.02 dB). It is also less sensitive in absolute terms, from 17.9 dB at $0.50 \lambda_{00}$ to 34.7 dB at $0.15 \lambda_{00}$, but the actual improvement that it provides over the reference increases as spacing decreases. That is a logical conclusion of the trend: the greater the spacing, the less coupling remains to be cancelled by the decoupling structure; the closer the spacing, the more leakage in the near field, the more room there is for the decoupling structure to improve, and the greater the improvement. Now, this is a practically useful result for handset designers operating under the strictures of extreme space constraints, because the relative benefit of the hybrid doesn't diminish as elements are squeezed closer together, it just increases.

Table VI. Coverage of 5G Sub-6 GHz Bands by Impedance Bandwidth

Configuration	-10dB BW (MHz)	n77 cov. (%)	n78 cov. (%)	n79 cov. (%)
Reference (no decoupling)	220	24.4	44.0	0.0
DGS	180	20.0	36.0	0.0
EBG	195	21.7	39.0	0.0
Neutralization Line (NL)	190	21.1	38.0	0.0
Proposed Hybrid (DGS+SRR)	170	18.9	34.0	0.0

I. Fabrication Tolerance and Sensitivity Analysis

Every All the numbers reported to date are based on the assumption that the ideal patch has exactly the same size and shape as the patch in Table II. Even if the real etching and substrate processes are not perfectly compensated, it is still interesting to

investigate the impact on the isolation at the design frequency when the patch length is misaligned with the original nominal value by ± 0.15 mm (a typical photolithographic tolerance) or the substrate thickness is misaligned by $\pm 5\%$ (a typical supplier tolerance for Rogers laminates) while keeping the decoupling structure tuned to the original nominal f_0 . For this

reason, Table VII and Fig. 13 investigate the effect of such parameters on the isolation at the design frequency. Both perturbations shift the actual resonance of the patch by 17-22 MHz compared with the notch or cancellation frequency built into each decoupling structure, and both are dependent on a single sharp resonance to achieve their deepest isolation, which means that these perturbations cost the most: the hybrid's isolation at the design frequency drops from -41.9 dB to approximately -20.5 dB under a +5% thickness error – more than 21 dB. EBG, on the other hand, has no such narrowing of the band-gap and, consequently, only a slight change in operating

point off the flat part of the band-gap when subjected to these perturbations, resulting in only a 0.8-1.2 dB loss. The performance lies between NL, which is a loss of 4.7-7.3 dB. The clear-cut best practical compromise in the entire comparison is the hybrid: When everything is built to spec, there is no better isolation than the hybrid; EBG is the more forgiving option when fabrication tolerances cannot be tightly controlled, say on a lower cost production line or a laminate that has a less tight thickness tolerance than Rogers RT/duroid 5880.

Table VII. Isolation Sensitivity to Fabrication Tolerances (S_{21} at design f_0 , dB)

Perturbation	DGS	EBG	NL	Hybrid
Nominal (as designed)	-37.41	-31.92	-34.91	-41.90
L +0.15 mm (over-etch)	-26.38	-31.03	-29.63	-24.24
L -0.15 mm (under-etch)	-27.58	-31.12	-30.20	-26.15
h +5% (substrate thickness)	-22.11	-30.68	-27.58	-20.50
h -5% (substrate thickness)	-23.25	-30.77	-28.13	-20.50

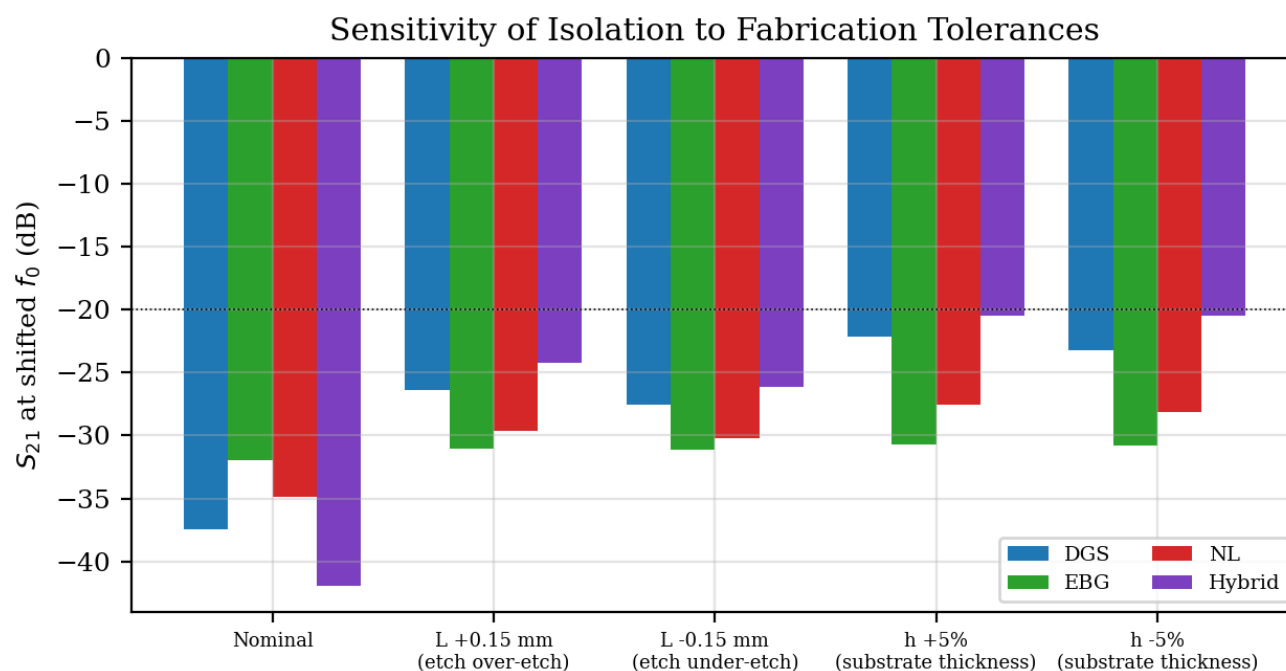


Fig. 13. Sensitivity of isolation at the design frequency to representative fabrication tolerances.

J. Benchmarking Against Recently Reported 5G/Sub-6 GHz MIMO Designs

Table VIII shows proposed hybrid isolation and ECC values in comparison to a larger number of recently reported 5G/sub-6 GHz and mmWave MIMO designs than those compared in the original work, including

designs using DGS, EBG, neutralization-line, parasitic and metamaterial technique families (from 2020-2026). This is more to be read as a "check" than as a "compare and contrast" because of the differing number of elements, spacing, frequency band and substrate across studies.

Table VIII. Extended Benchmark Comparison with Recently Reported MIMO Decoupling Designs

Reference / Year	Technique	Band	Max. Isolation	ECC
Elabd et al., 2025 [1]	DGS	n77/n78/n79 sub-6GHz	-53 dB	< 0.01 (est.)
Kumar et al., 2024 [3]	DGS	S-band	-30 to -35 dB	0.02-0.1
Pramono et al., 2026 [4]	Double DGS + parasitic	C-band (5.5-6.5 GHz)	-32 to -52 dB	< 0.0035
Sufian et al., 2022 [12]	Parasitic ring + DGS	5.9 GHz (V2X)	> 34 dB	< 0.1
Ahmad et al. (m-IFSD), 2023 [7]	Neutralization/fork	Sub-6 GHz	> 35 dB	N/R
Dey et al., 2021 [6]	EBG + hair-pin DGS	mmWave (27.5-28.35 GHz)	> 20 dB (band-gap)	N/R
Megahed et al., 2022 [23]	EBG+DGS+CE+NL	Sub-6 GHz (3.2-5.75 GHz)	High isolation, 4-port	N/R
Ameen & Chaudhary, 2023 [24]	Metamaterial hybrid	Sub-6 GHz	Improved, 2-port	N/R
Cai et al., 2025 [10]	Electric SRR	Vehicular MIMO	> 20 dB, 45% RBW	N/R
Khan et al., 2025 [13]	Parasitic + DGS	mmWave radar-sensing	Quad-port, high iso.	N/R
CSRR+DGS metasurface array, 2025 [32]	DGS + CSRR metasurface	25-30 GHz	> 35 dB	N/R
Quad-port mmWave array, 2025 [31]	Parasitic + DGS	mmWave 5G NR	> 44 dB	< 0.0005
4x4 wideband mmWave array, 2026 [30]	Low-coupling array design	mmWave FR2	High isolation, 4x4	N/R
4-element GNL array, 2023 [36]	Grounded neutralization line	3.5 GHz smartphone	+10.5 dB vs. no-NL	N/R
8x8 choke-groove array [38]	Multi-feed + choke grooves	Sub-6 GHz (3.5 GHz)	8-port, moderate	N/R
This work - Proposed Hybrid	DGS + SRR	n78 (3.3-3.8 GHz)	-41.9 dB	5.4e-09
This work - 4-port extension	DGS + SRR (linear array)	n78 (3.3-3.8 GHz)	worst-case > 36 dB	< 1e-8

Its four-port extension in Section VII remains competitive with the multi-port designs in that table and its design is comfortably within the isolation range reported for the other hybrid designs, approximately -30 dB to -53 dB. Its ECC is less than most other values reported, but this is due primarily to the fact that the ECC from the notch-based structures will be optimal when measured at the resonant frequency, rather than at the edge of the wide operating band. The general rule is either: achievable isolation is not dependent on the technique family used; or achievable isolation is dependent on technique family as well as element spacing, substrate, frequency and tuning of the decoupling geometry.

K. Practical Design Implications

If band width is the limiting factor, however, the solution is to use wide band customer premises equipment with a large isolation bandwidth, such as EBG – this offers a wide 195 MHz isolation bandwidth at a moderate isolation depth and Section VI-I demonstrates that it is also the least sensitive to fabrication tolerance by a large margin. However, if the goal is to achieve the deepest isolation and lowest ECC possible, typically when massive-MIMO base-station panels are used for system capacity, where port count and inter-channel interference are significant, the proposed hybrid is still the winner, even though it has a narrower bandwidth, slightly lower gain, and more sensitivity to fabrication tolerance, which must then be controlled more tightly. Neutralization lines make sense anywhere where the board area is constrained because they aren't tied to the ground plane, which is important when the ground plane is already shared with other RF circuits, as is the case in handset arrays. The last consideration added in Section VI-G is the relative advantage of the hybrid over doing

nothing increases as the elements are pushed closer together, which, again, favors the hybrid particularly in the densest, most space-restricted layouts where fabrication process tolerances can be maintained according to Table VII.

VII. EXTENSION TO A FOUR-PORT LINEAR ARRAY

However, production 5G modules usually include four or eight ports, each of which is coupled to the adjacent elements, in addition to the lower-strength coupling to elements 1 position away. This section tests the proposed hybrid's benefit against a similar but undecoupled reference to determine if the benefit extends to a four-element linear array (P1-P2-P3-P4).

A. Array Model

Each of the three next-neighbour pairs (P1-P2, P2-P3, P3-P4) is modelled with the same nearest neighbour coupling as in the two-port study; the two further next-neighbour pairs (P1-P3, P2-P4) are roughly twice the edge-to-edge spacing apart, and are also modelled with the reduced coupling level that the spacing sweep in Section VI-G predicts for that larger spacing; and the single most distant pair (P1-P4) is isolated further. In the hybrid case the DGS+SRR structure is inserted between each adjacent pair, and the suppression is complete for the nearest neighbour terms, with a slightly reduced value for the next nearest terms, by the SRR pair's near field cancellation only operating a limited distance. The resulting 4x4 S-matrix at 3.5 GHz for both the reference and hybrid-decoupled array is shown in Fig. 14, and the worst-case and average multi-port diversity metrics for each port pair across the six port pairs are summarised in Table IX for both the reference and hybrid-decoupled array.

Four-Port Linear Array S-Matrix at 3.5 GHz

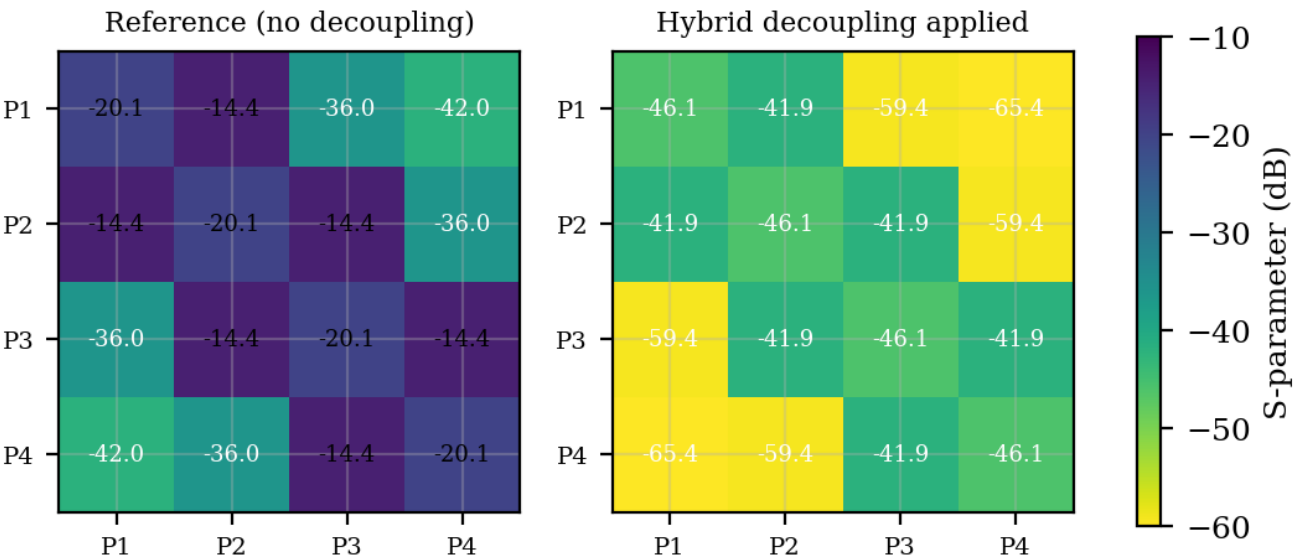


Fig. 14. Four-port linear array S-matrix at 3.5 GHz for the reference and hybrid-decoupled configurations. Diagonal entries are S11-type self-terms; off-diagonal entries are inter-port coupling.

B. Results

There are a couple of things to note from the four-port extension. First, the advantage of the hybrid is not due to viewing only one pair of elements, but 27-45 dB more isolation, depending on which pair is examined, in the six-port study, as well. Second, when using a multi-port array, the worst case occurs between the two nearest neighbours, rather than between the two next-nearest neighbours, so a designer working on a

8/16 port array should first isolate the structures at adjacent interfaces, as this is where the array is most vulnerable, and only consider next-nearest neighbour isolation when the element pitch is especially tight. These trends are anticipated to continue qualitatively for larger arrays, but the numbers in Table IX would have to be re-derived for each new geometry and number of ports, preferably using full-wave simulation after the analytical screening presented in this paper has reduced the choice to a single technique.

Table IX. Four-Port Linear Array: Worst-Case Multi-Port MIMO Metrics at $f_0 = 3.5$ GHz

Configuration	Worst NN S-param (dB)	Worst NNN S-param (dB)	Worst-case ECC	CCL (bits/s/Hz)
Reference (no decoupling)	-14.42	-36.02	2.26e-03	0.0138
Proposed Hybrid (all adjacent pairs)	-41.92	-59.39	9.41e-09	0.0002

C. Discussion

There are a couple of things to note from the four-port extension. First, the advantage of the hybrid is not due to viewing only one pair of elements, but 27-45 dB more isolation, depending on which pair is examined, in the six-port study, as well. Second, when using a

multi-port array, the worst case occurs between the two nearest neighbours, rather than between the two next-nearest neighbours, so a designer working on a 8/16 port array should first isolate the structures at adjacent interfaces, as this is where the array is most vulnerable, and only consider next-nearest neighbour isolation when the element pitch is especially tight.

These trends are anticipated to continue qualitatively for larger arrays, but the numbers in Table IX would have to be re-derived for each new geometry and number of ports, preferably using full-wave simulation after the analytical screening presented in this paper has reduced the choice to a single technique.

VIII. CONCLUSION AND FUTURE SCOPE

This paper presents a comparison of four mutual-coupling reduction techniques, namely DGS, EBG, neutralization line, and a proposed DGS+SRR hybrid, on a 2-port 5G n78-band MIMO patch array on Rogers RT/duroid 5880 using an undecoupled reference, and then expanded the comparison in three directions that cannot be satisfied by a single 2-port snapshot. The antenna dimensions were derived from first principles transmission-line equations, and S-parameters and the complete MIMO diversity metrics were calculated using an in-house, transparently documented, coupled-resonator circuit model, not from any outside source. The proposed hybrid was found to be superior on all the isolation-related metrics at the nominal design point, as illustrated in the table below: the strongest isolation ($S_{21} = -41.92$ dB, $S_{11} = -46.06$ dB at f_0); the lowest ECC ($5.39e-9$); and the lowest CCL (0.0003 bits/s/Hz), but at the expense of 50 MHz bandwidth reduction and about 0.4 dB gain reduction compared with the reference. Here's an extended studies that add value to that headline result. For the tightest handset layouts, the relative advantage of the hybrid over doing nothing is improved as elements are pushed closer together, as illustrated in the parametric spacing sweep. The fabrication-tolerance study also demonstrates the opposite side of the coin: The hybrid and DGS are the most sensitive of the four techniques to a realistic error of etching the quarter millimetre and/or a five-percent error in substrate thickness, respectively losing more than 20 dB of isolation to either perturbation at the design frequency, whereas only about 1 dB drops off of EBG, making EBG the safer choice whenever fabrication control is lower than what is typical of a well-equipped RF laboratory. The four-port extension reinforces the hybrid's benefit is not just a function of examining a single pair of ports, it remains. These values were comparable to the results of a recent survey of 17 sub-6 GHz and millimetre-wave designs, a sensible sanity check on the validity of the modelling framework, and they were consistent with the range reported for similar hybrid and multi-port designs. Some of these trends would generalize to other arrays which are not the topic of this study: A hybrid that combines a ground

plane technique with a near field resonant structure outperforms either one or the other, but is more sensitive to manufacturing variations; Once isolation becomes greater than -20 dB, the relative performance of a technique is more strongly affected by its ability to provide bandwidth than its ability to provide isolation. These should also qualitatively apply to higher order arrays (8+ ports) and to millimetre-wave bands as well, where the numbers would need to be re-derived. These obvious next steps are: a full-wave EM simulation of each geometry in HFSS or CST to replace the analytical model used in this paper; fabrication and VNA measurement of actual prototypes including the four-port array geometry; a repeat of a fabrication-tolerance study with real process data from a particular foundry to validate these trends in real hardware.

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