Frequency Reconfigurable MIMO antenna: previous advancements

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Abstract. This paper presents a comparative study of six recent publications on frequency-reconfigurable MIMO antennas for wireless communications, covering works published between 2019 and 2023. The reviewed designs span PIN-diode switching, varactor-based continuous tuning, and band-notch reconfiguration strategies, targeting 4G LTE, sub-6 GHz 5G, Ultra-Wideband (UWB), WLAN, WiMAX, and cognitive radio applications. Key performance metrics are systematically compared: gain ranges from 1.15 to 7.7 dBi, radiation efficiency from 60% to over 85%, port isolation from 12 to 30 dB, and Envelope Correlation Coefficient ECC from less than 0.001 to 0.2 Results show that PIN-diode designs dominate current implementations due to their low cost and fast switching speed. Among the reviewed works, reference [1] achieves the best balance of ECC, isolation, fabrication simplicity for sub-6 GHz LTE/5G applications, while reference [2] offers superior isolation (>30 dB) and ultra-low ECC (<0.001) for UWB scenarios. Persistent challenges include switching losses, mutual coupling in compact arrays, and discrete tuning limitations, with future research converging on RF MEMS, AI-driven reconfiguration, and SDR integration.

Keywords: MIMO antenna; frequency reconfigurable; PIN diode; sub-6 GHz; UWB; 5G; WLAN; cognitive radio.

1. Introduction

The rapid evolution of wireless communication standards, spanning 4G LTE, sub-6 GHz 5G New Radio (NR), Ultra-Wideband (UWB), WiMAX, and cognitive radio, has imposed increasingly stringent requirements on antenna front-ends. Multiple-Input Multiple-Output (MIMO) antenna systems have emerged as the predominant solution for achieving high channel capacity and spatial diversity without additional bandwidth or transmit power [3]. However, conventional fixed-frequency MIMO designs cannot accommodate the dynamic spectrum-access requirements of modern multi-standard terminals.

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Frequency reconfigurability can be introduced by embedding active switching elements, namely PIN diodes, varactor diodes or RF MEMS switches, within a single MIMO aperture to select the most suitable frequency band on a system-by-system basis [4].In most compact MIMO implementations, PIN diodes are the preferred option due to their low cost, high switching speed, and planar fabrication feasibility [5].also it have a strong mutual coupling among individual antennas severely increases the Envelope Correlation Coefficient (ECC) and consequently deteriorates diversity performance. To counteract these effects, a variety of decoupling techniques have been recently proposed in the literature and thoroughly analysed, including defected ground structures (DGS), parasitic stubs, and neutralization lines [6],[7]. In this paper six representative papers are reviewed, compared and analysed in a systematic and structured way. The design choices as well as the performance trade-offs of the respective solutions are analysed, evaluated and discussed for the different application fields. Suitable solutions and open research challenges are revealed.

2. Study Scope and Objectives

The primary purpose of this research work is to conduct a comparative analysis of the various types of frequency-reconfigurable MIMO antennas. For this purpose, the work has been constrained to a few papers recently published on the above topic. In choosing which papers to include in the analysis, certain criteria have been adopted by this work. These criteria include the operating frequency band of the antenna (sub-6 GHz or UWB); the mechanism used for frequency reconfigurability (i.e., PIN diode switching, varactor-based tuning, etc.); and the period during which the corresponding articles were published (2019-2023). Six established performance metrics have been considered for comparing the performance of the different designs under the following six headings: Frequency-reconfigurability mechanism; Operating frequency band; Antenna gain; Antenna radiation efficiency; Port isolation and return loss; and Envelope Correlation Coefficient (ECC) of MIMO configuration.

3. Methodology

The selected papers are different in terms of diversity in reconfigurability, different types of antenna configurations and also different applications, which include LTE, 5G, WLAN, WiMAX, UWB and cognitive radio communications. In order to compare the performance of the selected articles, a comparison grid that consists of six performance categories was designed. The comparison grid was made to apply to all the selected articles in a totally standardised manner. The selected articles for this study are listed in Table 1.

Table 1. Summary of selected articles.

Ref	Authors	Journal/ Year	Antenna type	Reconfiguration	Application	Key results
[1]	Pant et al.	IJEC 2021	2×2 MIMO	2× PIN diodes	LTE / early 5G	2.4 GHz ↔ 3.5 GHz, compact, high isolation
[2]	Nej et al.	AEÜ 170 2023	2×2 UWB MIMO	U-slot + PIN + DC cap	UWB / 5G / Radar / IoT	Flexible notch, high isolation, easy fabrication
[8]	Jin et al.	IEEE Access 2019	Single-element	PIN diodes	WLAN / sub-6 GHz 5G	Good symmetry & common-mode rejection
[9]	Riaz et al.	Wiley OL 2019	2-el. MIMO	Varactor (agile feedline)	Cognitive radio (CR)	Tunable 1.8–3.5 GHz, high isolation, low coupling

[10]	Gupta & Bage	TJAPT 2023	2×2 & 4×4 MIMO	PIN diodes	5G / WLAN / WiMAX	2.4/3.5/5.8 **GHz**, isolation >20 dB, ECC <0.02
[11]	Durukan & Altuncu	AEÜ 170 2023	4×4 UWB MIMO	RF switches + stubs (PIN)	UWB / Cognitive / IoT	3 modes, adjustable notches, compact

4. Comparison and Analysis

A criteria-based comparison approach was applied to each of the designs reviewed above. The comparison of the antenna geometry itself and the employed reconfiguration method as well as the frequency coverage of the designs and the resulting MIMO performance metrics are the main aspects that have been considered in the above comparison approach. The principal performance metrics for all the considered antennas are summarized in Table 2.

Table 2. Performance metrics.

Ref	Antenna	Reconfiguration	Freq. Range	Gain	Eff.	RL / Isolation	ECC	Application
[1]	2-el. MIMO, meandered monopole	PIN diodes	2.0–2.7 GHz (4G) / 2.57–4.27 GHz (5G)	3.7–4.6 dBi	64–94%	RL < −31 dB / >12–19 dB	<0.006	4G LTE / 5G sub-6
[2]	2-el. MIMO, 6 switchable notch modes	U-slot + PIN + DC cap	UWB 2–12 GHz ; notches 3.5/4.5/7.5 GHz	1.15–5.23 dBi	>85%	VSWR ≤ 2 / < −30 dB	<0.001	UWB / 5G / Radar / IoT
[8]	Single-el., stacked patch, diff. feed	PIN diodes	2.37–2.67 / 3.39–3.62 GHz	6.5–7.7 dBi	64–70%	RL < −10 dB / —	N/R	WLAN / sub-6 5G
[9]	2-el. MIMO, hexagonal patch	Varactor (agile feedline)	1.42–2.27 GHz	−0.2 to 2.2 dBi	60–78%	RL < −6 dB / >12 dB (DGS)	<0.2	Cognitive radio
[10]	2×2 & 4×4 MIMO, L-shaped patches	PIN diodes	2.57–6.18 GHz (ON) / 4.85–6.16 (OFF)	2.4–3.6 dBi	>85%	RL < −38 dB / >17 dB	<0.05	5G / WLAN / WiMAX
[11]	4×4 MIMO, symmetric orthogonal	RF switches + stubs (PIN)	3.1–12.1 / 8.38–11.66 / 2.9–10.56 GHz	1.09–5.73 dBi	N/R[1]	RL < −10 dB / ≥18.6 dB	<0.006	Cognitive / UWB / IoT

[1] N/R = Not Reported in the original publication. [8] is a single-element design; MIMO diversity metrics (ECC, isolation) are not applicable and are intentionally omitted.

4.1. Antenna Configuration

A single element as well as multi-element MIMO designs have been implemented and tested for a variety of applications. The work [8] presented a dual-layer stacked patch design, that utilised differential feeding in order to counter common mode signals as well as to provide two frequencies of operation for the single-port structure.in [9] and [11], a 2×2 MIMO configurations were presented for a number of sub-6 GHz frequency bands. These included, hexagonal shaped patches, meandered monopoles as well as cross-shaped and L-shaped patches. Works [2] and [11] presented 4×4 as well as 2×2 UWB MIMO structures, with the wide spectral range the main design goal for these structures. A band-notch had been selectively introduced in the pass-band for a number of applications including radar, IoT as well as satellite communications.

4.2.Reconfiguration Mechanisms

Five designs used PIN diodes, [1], [2], [8], [10],and [11]. The use of PIN diodes in these designs is due to the low forward-bias resistance, the fast-switching time, and the planar integration which makes them easy to implement in planar circuits. The design in [9] used varactor diodes instead of PIN diodes. The varactor diodes are integrated into an agile microstrip feedline in order to continuously tune the frequency between 1.42 GHz and 2.27 GHz. PIN-diodes are mainly used as a binary (on/off) switch. In contrast to that, the varactor diodes in this design can be controlled in a continuous manner. In addition to PIN diodes, designs [2] and [11] used RF-stubs and DC-blocking capacitors to implement a band-notch in the UWB band. The number of switching states in these designs are ranging from 2 (for a binary on/off switch) up to 6 different modes in [2]. While more modes allow for more flexibility in the spectrum, they also increase the complexity of the design.

4.3.Frequency Range and Coverage

The designs [1], [8], and [10] have the optimal frequency range of 2.0 GHz to 6.2 GHz, and can be thus utilised for 4G LTE, WLAN (2.4 GHz/5.8 GHz), or 5G NR in frequency bands n77 and n78. Among the frequency ranges of sub-3-GHz in [9], the largest tuning range of 1.42 GHz to 2.27 GHz can be effectively used for the spectrum sensing of the cognitive radio. In addition, the designs in [2] and [11] have frequency ranges of 2 GHz to 12 GHz of the entire UWB spectrum, and, in addition, frequency ranges of the configurable notch bands of 3.5 GHz (WiMAX), 4.5 GHz (sub-6 5G), and 7.5 GHz (satellite) in the spectrum, and thus are clearly more versatile than the other works.

4.4.Performance Metrics

Gain values range from 0.2 dBi [9], (limited by varactor insertion loss) to 7.7 dBi ([8], benefiting from the stacked patch and differential feeding topology). UWB designs [2] and [11] report moderate average gain (1.09–5.73 dBi). The relation between bandwidth and gain is evident in these papers. Specifically, radiation efficiency was reported to be above 85% in the works by [2] and [10], while [9] indicated a lower range, between 60% and 78%, which was primarily a consequence of varactor losses and the intricate design of the feedline. Note that [11] does not report efficiency in the original publication. Port isolation is highest in [2] (>30 dB), followed by [11] (>18.6 dB) and [10] (>17 dB). ECC is lowest in [2] (<0.001), well below the 0.5 standard threshold, confirming excellent spatial decorrelation.

4.5.Strengths and Weaknesses

Table 3 summarises the strengths and weaknesses of every design. the single-element single-port antenna design in [8] was only considered because it is reconfigurable. As for the other criteria that are typical for the evaluation of MIMO antennas, ECC, port isolation, etc., for single-port designs they are not relevant. Among the selected designs, the design in [1] is good for use in LTE/5G communication at frequencies for sub-6 GHz, since the ECC value is good (<0.006), the isolation value is high (>19 dB), the design is easy to implement (single layer), and there is a wide frequency range covered. For UWB and multi-application uses, work [2] achieves exceptional isolation (>30 dB) and low ECC (<0.001) and flexible 6-mode band-notch control with a higher cost of fabrication complexity.

Table 3. Strengths and weaknesses.

	[1]	[2]	[8]	[9]	[10]	[11]
Strengths	Wide BW, isolation >19 dB, RL −31 dB, low ECC	6 notch modes, isolation >30 dB, ECC <0.001	Diff. feeding, dual-band, high gain (7.7 dBi)	Continuous tuning, DGS isolation, compact layout	Dual-band, efficiency >85%, isolation >17 dB	UWB flexibility, 3 modes, isolation >18.6 dB
Weaknesses	Moderate gain (≤4.6 dBi); cost	Moderate gain (≤5.23 dBi); fabrication complexity	Single-element, no MIMO diversity metrics (ECC/isolation N/A)	Lowest gain (−0.2 dBi), poor RL (−6 dB), moderate ECC (<0.2)	Multiple PIN diodes increase design complexity	Efficiency not reported; complex bias routing

5. Challenges and Future Directions

Frequency-reconfigurable MIMO antennas face several problems and challenges, that constrain their practical implementation. The use of PIN diodes as switching elements introduces resistive losses, parasitic reactance, and nonlinear distortion that degrade radiation efficiency, particularly at higher frequencies. In compact MIMO layouts, the proximity of radiating elements intensifies mutual coupling, raising the ECC and compromising diversity gain in a manner that varies across switching states, making uniform isolation across all operating bands difficult to achieve. The binary nature of PIN-diode switching further restricts operation to discrete frequency bands, which is insufficient for dynamic spectrum environments such as cognitive radio. Additionally, individual DC bias lines and continuous forward-bias current, typically 10–30 mA per diode, impose layout complexity and power overhead that are prohibitive in energy-constrained IoT and mobile platforms.
Several research directions are expected to address these limitations. RF MEMS switches and liquid-metal reconfigurable structures promise near-zero standby power and superior linearity, eliminating the nonlinearity constraints of semiconductor-based designs. Advanced decoupling techniques including metamaterial-based electromagnetic bandgap (EBG) [12], structures and characteristic mode-based antenna topologies, aim to achieve configuration independent high isolation. At the system level, the integration of machine learning-driven reconfiguration algorithms with Software-Defined Radio (SDR) platforms will enable fully adaptive multi-standard operation. Finally, phase-change materials such as vanadium dioxide (VO^2) [13], which transition between insulating and conducting states without requiring continuous bias current, represent a compelling pathway toward energy-autonomous reconfigurable MIMO systems.

Conclusion

In this work, a systematic comparative study was conducted on six recent frequency-reconfigurable MIMO antenna design papers from 2019 to 2023. In particular, we found a distinct performance stratification, whereby pin diode designs give a good trade-off between isolation, ECC, and fabrication costs for below 6 GHz applications, where the best choice is [1], providing the best ECC (ECC <0.006), isolation (>19 dB), and can be fabricated used only a single layer PCB. Varactors, on the other hand, can support tunability continuously at

the cost of a lower gain/efficiency. Finally, the UWB band-notch designs of [2] offer excellent isolation (>30 dB) and ECC (<0.001).
However, in light of current challenges in terms of switching losses, mutual coupling in compact arrays, tuning discreteness, and power overhead issues, the future directions in the field of research include the RF MEMS switching, AI driven antenna reconfigurability and SDRs. With an increasing demand for more bandwidth due to growing numbers of 5G and even 6G communication systems as well as IoT, frequency-reconfigurable MIMO antennas will remain one of the key technologies with room for improvement in materials science and intelligent control.

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