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REGULAR ARTICLE

Compact Snow-Flex Structured MIMO Antenna Architecture with Enhanced Isolation for 2.48 GHz Wireless Sensor Networks

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This work presents a compact snow-flex structured MIMO radiator for wireless sensor network applications. The designed structure is simulated on an FR-4 dielectric substrate material with an overall size of 80 mm × 45 mm, making it suitable for compact wireless devices. It operates at a resonant frequency of 2.48 GHz covering 2.46 to 2.51 GHz, which supports the ISM band for WSN communication. The simulated S_{11} of − 32.90 dB confirms excellent impedance matching. The isolation among MIMO system is − 26.64 dB (S_{21}), demonstrating effective suppression of mutual coupling. A spacing of 3 mm is maintained between two radiator elements to further reduce electromagnetic interference by offering improved isolation. The key MIMO performance metrics as Envelope type Correlation Coefficient (ECC), Diversity related Gain (DG), Channel related Capacity Loss (CCL) and Total Active type Reflection Coefficient (TARC) are thoroughly calculated and discussed. All MIMO parameters satisfy the standard requirements for reliable wireless communication systems. The results indicate strong diversity performance, low correlation, and high channel capacity. Hence, designed MIMO radiator is a promising candidate for compact and efficient WSN and ISM band wireless applications.

Keywords: MIMO, Mutual coupling, Channel capacity loss, Wireless sensor networks, Return loss.

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1. INTRODUCTION

The noticeable growth in modern high data rate systems has accelerated the necessity of MIMO antennas to meet the supplicated features of advanced wireless networks, which includes higher capacity, better network coverage, and faster data rates with reliable communications A remarkable progress has been observed in design methodologies of MIMO antennas, as reported in literature. Some reported works include, a MIMO antenna with double sided design for UWB system, which provides improved isolation [1], a CPW fed MIMO system analyzed and designed with parasitic elements [2], MIMO radiator improved isolation and return loss the requirement of C band spectrum [3], design of Minkowski MIMO radiator for supporting multi-band system [4], a small, flexible 8 port MIMO antenna with I-shaped radiator designed wide band sub-6GHz system [5], 2-element four port MIMO system for portable systems [6], fractal MIMO antenna with deep learning optimization and CMA analysis [7], circular and rectangular fractal strip based MIMO radiator for sub-6 GHz 5G regions [8], achievement of broad band operation in MIMO antenna with coaxial feeding [9], a 8-port system of UWB designed for 5G array system [10], a half-circular dual-band U-shape MIMO system designed for region of wireless systems [11], for the region of 5G smart phone, design of a wideband PIFA system is reported in [12], 6-port MIMO system for the regions of LTE, carrier generation and Wi-Fi systems [13], an array structure of MIMO antenna is designed with TARC analysis, and mutual coupling reductions [14], a 4-element mm wave MIMO antenna system for future generation [15], a 4-port extendable MIMO system with improved isolation [16], design of parasitic elements based 9-shaped MIMO structure for mutual coupling reduction [17].

This work presents a compact snow-flex structured MIMO antenna, designed to operate at the 2.48 GHz, specifically targeting the wireless sensor network applications. The proposed antenna achieves high isolation and the excellent impedance matching while maintaining a small footprint, making it suitable for low-power and also the space-constrained wireless devices. The main novelties of this work include the introduction or overview of the a compact snow-flex structured MIMO radiator specifically tailored for the wireless sensor network and also the ISM band applications, offering a most efficient combination of miniaturization and high isolation. The achievement of these high-performance MIMO metrics on FR-4 substrate of low-cost with a compact footprint of 80 mm × 45 mm highlights the design's practicality, cost effectiveness, and suitability for real-time WSN and ISM band wireless communication systems.

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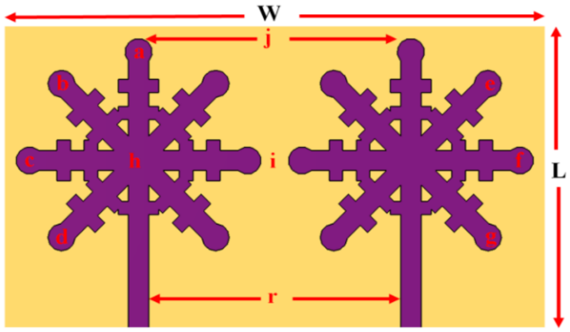
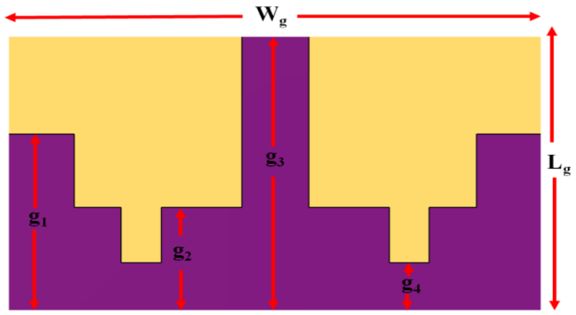
2. ANTENNA TOPOLOGYAND GEOMETRY

Fig. 1(a) illustrates the top view of a two-element MIMO antenna printed on a rectangular substrate, where the yellow region represents the dielectric material and the purple areas correspond to the metallic radiating structures. The parameters W and L define the overall width and length of the antenna substrate. Each antenna element is designed with a snowflake or star-shaped radiator consisting of multiple arms (a, b, c, d, e, f, g, etc.), which effectively increase the current path length, enabling compact size and resonance at the desired operating frequency.



(a)



(b)

Fig. 1 – Snow-flex structured MIMO design (a) Upper view (b) Lower view

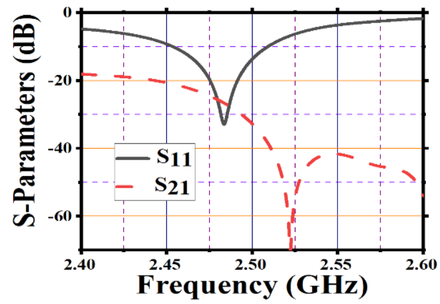
The vertical purple strips connected to each radiator function as feeding lines that excite the radiating elements. The parameter r denotes center-to-center spacing among 2-antenna elements and plays a crucial role in controlling mutual coupling in the MIMO configuration. The region marked with symbol 'i' indicates the inter-element separation area, which contributes to enhanced isolation by reducing surface current interaction between the radiators, while j represents the effective horizontal span over which surface currents and electromagnetic fields are distributed across the antenna structure.

Table 1 – All structural dimensions of the snow-flex design and measured in mm.

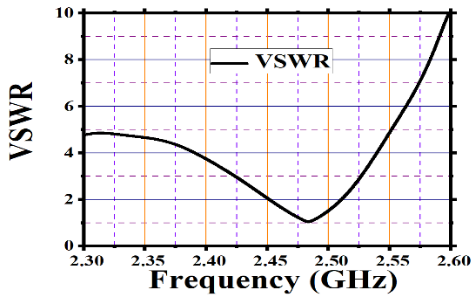
W	L	a	b	c	d	W_g	L_g	e	f
80	45	3	3	3	3	80	45	5	3
g_1	g_2	g_3	g_4	g	h	i	j	r	ε_r
30	20	45	5	3	8	3	20	24	4.3

Fig. 1(b) illustrates the dimensional configuration of the stepped ground plane structure used in the antenna design, where yellow region represents substrate and purple area indicates the metallic ground. The parameter W_g denotes the total width of the ground plane, while l_g represents its overall length. The central vertical extension labeled g_3 acts as a modified ground stub, which plays significant role in tuning impedance matching and improving isolation by controlling surface current distribution. The stepped sections on both sides are defined by the heights g_1, g_2 and g_4 which introduce discontinuities in the current path and help suppress unwanted coupling between antenna elements. These geometrical variations effectively modify the ground plane behavior enhancing bandwidth, improving impedance characteristics and contributing to better MIMO performance by reducing mutual coupling and stabilizing radiation characteristics. Fig. 2 (a) presents the simulated s-parameters of MIMO structure function of frequency in the 2.40-2.60 GHz band illustrating matching impedance and isolation performance. the solid black curve represents S_{11} which indicates antenna performance and shows a deep resonance around 2.46-2.51 GHz, where the value drops below – 10 dB confirming efficient power radiation and better impedance matching at the operating frequency. the dashed red curve corresponds to S_{21} which represents the transmission. the very low S_{21} reaching below 25 dB and even approaching – 60 dB near resonance coupling ensures minimal interference and correlation between antenna ports, thereby enhancing over all MIMO system performance in terms of diversity and channel capacity.

Fig. 2 (b) illustrates the VSWR of the current designed structure. The VSWR at the resonant frequency equals 1. The attainment of minimum VSWR signifies perfect impedance matching. On the other hand, the VSWR remains within 2 over the entire operating band.



(a)



(b)

Fig. 2 – Snow-flex structured design (a) S-parameters (b) VSWR

Fig. 3 (a) illustrates surface current distribution of proposed snow-flex structured MIMO device when excited by Port_1 and the other port is matched load termination. It can be observed that strong current concentration is mainly confined to the excited radiator particularly along the feed line and the arms of the snow-flake shaped structure, indicating effective radiation and proper excitation of the antenna element. In contrast, the induced current on the adjacent radiator is significantly weaker which confirms excellent isolation between the two MIMO elements. The color scale varying from red to blue represents magnitude related to surface current density in dB, where red denotes maximum current and blue indicates minimum current. The minimal current coupling on the non-excited element demonstrates the effectiveness of the compact spacing and structural design in suppressing mutual coupling. Hence, this figure validates the high isolation performance and efficient electromagnetic decoupling achieved by Reflection Coefficient designed MIMO antenna configuration. Similarly, Fig. 3 (b) illustrates surface current distribution of the proposed snow-flex structured MIMO antenna when excited by Port_2 and the other port matched load is terminated. Fig. 3 (c) illustrates the radiation pattern of designed structure *E*-field and *H*-field radiation patterns.

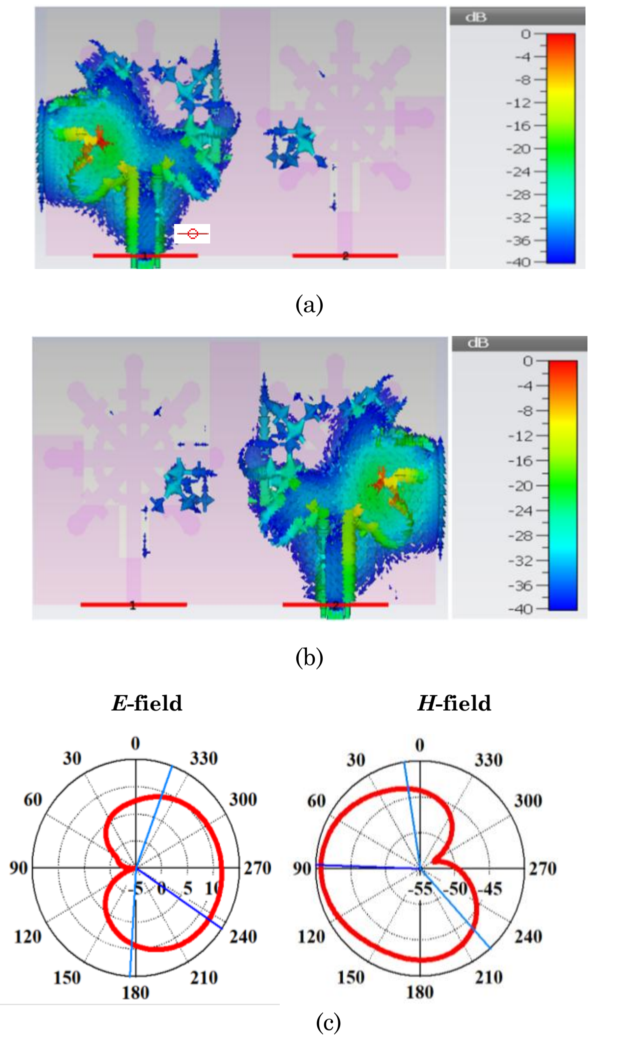


Fig. 3 – Snow-flex structured design: surface current distribution with (a) Port_1 mode of Excitation (b) Port_2 mode of Excitation and (c) Radiation patterns (*E*- and *H*-planes)

3. MIMO PARAMETERS EVALUATION

Several MIMO diversity metrics are also employed to evaluate the performance of proposed MIMO system in multipath propagation environments cases. The ECC quantifies level of independence between multiple antenna ports in wireless communication systems, where a lower ECC value signifies better port isolation and improved diversity behavior of the designed MIMO radiator.In this work, the ECC is determined using equation (1) to validate the effectiveness of the proposed structure, and the obtained values remain within the permissible limits across the operating frequency bands indicating optimal antenna performance. An alternative method for ECC estimation is also adopted using equation (2). Fig. 4 (a) illustrates simulated ECC results. For efficient diversity operation in MIMO systems, the ECC value must be less than 0.05 and the simulated ECC of designed structure is found to be ≤ 0.0109 which clearly satisfies this requirement and confirms its suitability for practical implementation. Furthermore, DG is an important parameter that enhances the signal-to-noise ratio in communication systems employing diversity techniques and is generally expressed in decibels (dB). Fig. 4 (b) presents the variation of diversity gain with frequency showing values close to 9.9999 dB around the resonant band. The calculation of DG from ECC is carried out using equation (3) as given in [12] which further confirm excellent diversity performance related to MIMO antenna.

$$ECC_{i,j} = \frac{\left|\iint_{4\pi}[\vec{E_i}(\theta,\phi).\vec{E_j}(\theta,\phi)d\Omega]\right|^2}{\iint_{4\pi}\left|\vec{E_i}(\theta,\phi)\right|^2 d\Omega \iint_{4\pi}\left|\vec{E_j}(\theta,\phi)\right|^2 d\Omega} \quad (1)$$

$$ECC_{i,j} = \frac{\left|S_{ii}^{*}S_{ij}+S_{ji}^{*}S_{jj}\right|^2}{\left(1-|S_{ii}|^2-\left|S_{ji}\right|^2\right)\left(1-\left|S_{jj}\right|^2-\left|S_{ij}\right|^2\right)} \quad (2)$$

$$\mathrm{DG}_{i,j}=10\sqrt{1-\left|\mathrm{ECC}_{i,j}\right|^{2}} \quad (3)$$

The TARC is important metric in MIMO designs and defined as square-root ratio related to overall reflected power by total incident power. It incorporates the effect of random excitation phases at all ports while accounting for mutual coupling between antenna elements. TARC acts an important role in characterizing radiation efficiency and impedance bandwidth of MIMO antennas under different excitation scenarios. In this study, TARC is evaluated using the formulation given in equation (4) [16]. Fig. 4 (c) illustrates the variation of TARC with frequency, where the values remain below − 10 dB at the resonant band confirming satisfactory radiation behavior of the proposed MIMO system.

$$TARC = \frac{\sqrt{\sum_{i=1}^{N}\left|S_{lm}+S_{lm}e^{j\theta_{m-1}}\right|}}{\sqrt{N}} \quad (4)$$

Channel capacity loss confirms critical diversity performance for MIMO system assessment. It helps to recognize maximum communication rate which is representing the chance of transmission of signals between the communication channel and operating frequency of signal loss parameters. The CCL acceptable value is < 0.2 bps/Hz [8]. The equations (5-7) determine expressions to perform CCL. The obtained CCL results are illustrated in Fig. 4 (d) remaining below 0.30 bps/Hz over all the resonant frequency bands.

$$C_{loss}=-\log_2 det(\Psi^R) \tag{5}$$

$$\rho_{ii} = 1 - \left(\sum_{j=1}^{8} \left|S_{ij}\right|^2\right) \tag{6}$$

$$\rho_{i,j} = -\left(S_{ii}^* S_{ij} + S_{ji}^* S_{jj}\right) \tag{7}$$

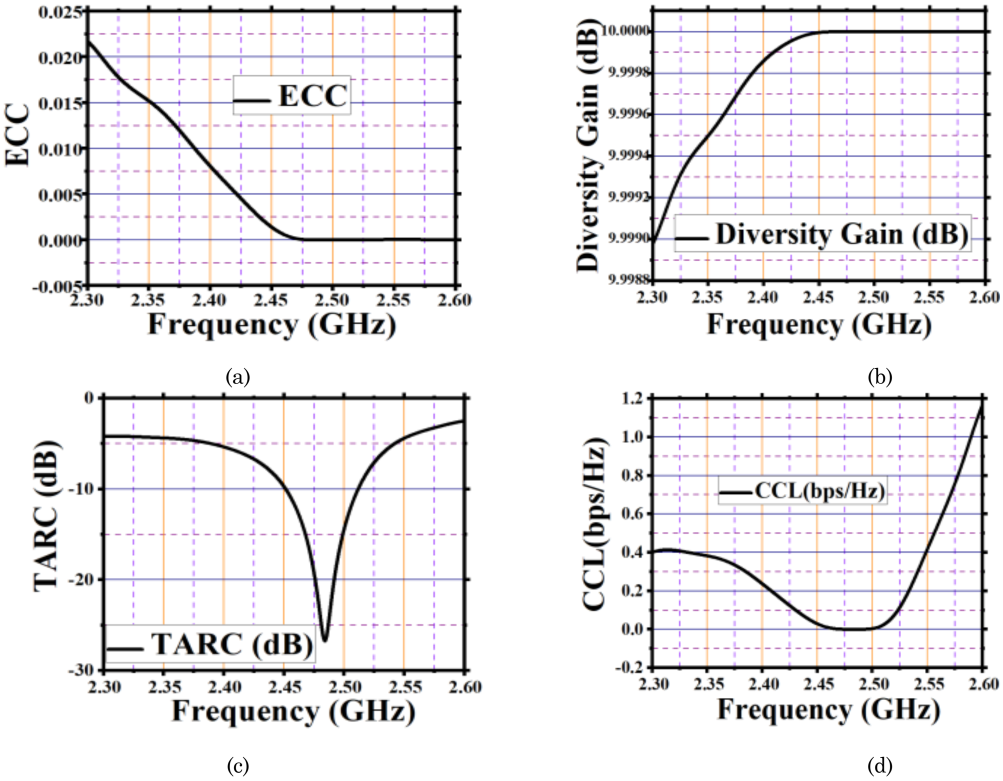


Fig. 4 – MIMO Parameter (a) ECC (b) DG (c) TARC (d) CCL

4. CONCLUSION

In conclusion, a compact snow-flex structured MIMO radiator has been successfully designed and analyzed for wireless sensor network applications operating in the ISM band. The antenna, implemented on substrate of FR-4 substrate with a compact footprint of 80 mm × 45 mm, demonstrates efficient operation at 2.48 GHz, ensuring suitability for space-constrained wireless devices. The achieved reflection coefficient of – 32.90 dB confirms excellent impedance matching, while the high isolation level of – 26.64 dB between antenna elements validates effective mitigation of mutual coupling. The optimized the 3 mm inter-element spacing further minimizes the electromagnetic interaction and also interference. Comprehensive evaluation of MIMO performance parameters, including ECC, DG, CCL, and TARC, shows that all values remain within acceptable limits, indicating strong diversity characteristics, low signal correlation, and enhanced channel capacity. These results confirm that the proposed MIMO radiator is a reliable and efficient solution for compact WSN and ISM band wireless communication systems.

REFERENCES

1. W.A.E. Ali, A.A. Ibrahim, *AEU-Int. J. Electron. Commun.* **82**, 7 (2017) https://doi.org/10.1016/j.aeue.2017.07.031.
2. K. Vasu Babu, G.N.J. Sree, S.V. Kumari, S. Das, *Design and Analysis of a CPW-Fed Fractal MIMO THz Antenna Using an Array of Parasitic Elements.* In: Terahertz Devices, Circuits and Systems (Eds. by S. Das, A. Nella, S.K. Patel), (Springer: Singapore: 2022) https://doi.org/10.1007/978-981-19-4105-4_4.
3. K.V. Babu, B. Anuradha, G.N. Jyothisree, *Int. J. Elect. Electron. Eng. Telecommun.* **6** No 2, 43 (2017) https://www.ijeetc.com/v6/v6n2/7_NCETEC014_(p.43-49).pdf.
4. K.V. Babu, B. Anuradha, *J. King Saud Univ.-Eng. Sci.* **32** No 1, 51 (2020).
5. Kulkarni, Neeta, Rajin M. Linus, Nilesh Bhaskarrao Bahadure, *AEU-Int. J. Electron. Commun.* **159**, 154479 (2023) https://doi.org/10.1016/j.aeue.2022.154479.
6. H.T. Chattha, *IEEE Access* **7**, 96516 (2019) https://doi.org/10.1109/ACCESS.2019.2925351.
7. K.V. Babu, S. Das, G.N.J. Sree, H.M.A. Almawgani, T. Islam, A.R.H. Alhawari, *Physica Scripta* **98** No 11, 115526 (2023) https://doi.org/10.1088/1402-4896/ad00e6.
8. G.N.J. Sree, S. Nelaturi, *Int. J. Commun. Syst.* **34** No 17, e4991 (2021) https://doi.org/10.1002/dac.4991.
9. K.V. Babu, G.N.J. Sree, S.V. Kumari, S. Das, *Recent Advances in Graphene Nanophotonics*, 351 (Cham: Springer Nature Switzerland: 2023).
10. X. Zhang, Y. Li, W. Wang, W. Shen, *IEEE Access* **7**, 72273 (2019) https://doi.org/10.1109/ACCESS.2019.2919622.
11. K.V. Babu, P.S. Rao, B.C. Naik, B.R. Kumar, *Microsyst.*

Technol. **29** No 4, 501 (2023) https://doi.org/10.1007/s00542-022-05359-9.
12. X-T. Yuan, Z. Chen, T. Gu, T. Yuan, *IEEE Antennas Wireless Propag. Lett.* **20** No 3, 371 (2021) https://doi.org/10.1109/LAWP.2021.3050337.
13. Y.V. Ram, S. Yadav P. Yadav, B. Mishra, A. Kumar, *AEU-Int. J. Electron. Commun.* **162**, 154576 (2023) https://doi.org/10.1016/j.aeue.2023.154576.
14. S.H. Chae, Se-K. Oh, S-O. Park, *IEEE Antennas Wireless Propag. Lett.* **6**, 122 (2007) https://doi.org/10.1109/LAWP.2007.893109.
15. A.M. Khan, A.G.A. Harbi, S.H. Kiani, A.N. Nordin, M.E Munir, S.I. Saeed, J. Iqbal, E.M. Ali, M. Alibakhshikenari, M. Dalarsson, *Appl. Sci.* **12** No 9, 4280 (2022) https://doi.org/10.3390/app12094280.
16. R. Utkarsh, M.K. Sharma, V. Singh, S. Javed, A. Sharma, *Optik* **247**, 167910 (2021) https://doi.org/10.1016/j.ijleo.2021.167910.
17. K.V. Babu, B. Anuradha, *Optical and Wireless Technologies: Proceedings of OWT 2019* (Springer: Singapore: 2020).

Компактна архітектура антени Snow-Flex Structured MIMO з покращеною ізоляцією для бездротових сенсорних мереж 2,48 ГГц

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У цій роботі представлено компактний MIMO-випромінювач зі структурою snow-flex для бездротових сенсорних мереж. Розроблена структура змодельована на діелектричній підкладці FR-4 із загальним розміром 80 мм × 45 мм, що робить її придатною для компактних бездротових пристроїв. Вона працює на резонансній частоті 2,48 ГГц, охоплюючи діапазон від 2,46 до 2,51 ГГц, що підтримує діапазон ISM для бездротового бездротового зв'язку. Змодельований S_{11}, що становить −32,90 дБ, підтверджує чудове узгодження імпедансу. Ізоляція між MIMO-системами становить −26,64 дБ (S_{21}), що демонструє ефективне придушення взаємного зв'язку. Між двома елементами випромінювача підтримується відстань 3 мм для подальшого зменшення електромагнітних перешкод шляхом покращення ізоляції. Ретельно розраховані та обговорені ключові показники продуктивності MIMO, такі як коефіцієнт кореляції обвідної (ECC), коефіцієнт підсилення, пов'язаний з рознесенням (DG), втрати ємності, пов'язані з каналом (CCL), та загальний коефіцієнт відбиття активного типу (TARC). Всі параметри MIMO відповідають стандартним вимогам до надійних систем бездротового зв'язку. Результати вказують на високу продуктивність рознесення, низьку кореляцію та високу пропускну здатність каналу. Отже, розроблений MIMO-випромінювач є перспективним кандидатом для компактних та ефективних бездротових застосувань у діапазонах WSN та ISM.

Ключові слова: MIMO, Взаємний зв'язок, Втрати пропускної здатності каналу, Бездротові сенсорні мережі, Втрати на відбиття.