# 4-Port Planar MIMO Antenna Using Open-Slot Radiators for 5G New Radio (NR) Frequency Bands n38 (2570 to 2620 MHz) and n41 (2496 MHz–2690 MHz) Applications

# Mohamed M. Morsy<sup>\*</sup>

Abstract—This article presents a compact, low profile, four ports multiple-input-multiple-output (MIMO) antenna operating at the n38 and n41 5G frequency bands. The antenna has a measured -10 dB bandwidth of 2.5–2.9 GHz with isolation less than -11 dB. The designed antenna system employs open slot radiators etched on a single-sided rectangular PCB substrate with a total size of  $40 \times 100 \text{ mm}^2$ , including a ground plane. The open slot radiators are symmetrically printed at the four corners of the rectangular substrate. The radiators are excited by  $50-\Omega$  strip lines. Rectangle-shaped slits are used as decoupling structures. MIMO parameters such as the envelope correlation coefficient (ECC), channel capacity loss (CCL), and mean effective gain (MEG) are calculated using the measured results. The ECC is less than 0.1 over the entire operating band despite the antenna's small size. The proposed antenna shows good performance in two sub-6-GHz frequency bands for 5G NR applications: n38 (2570 to 2620 MHz) and n41 (2496 MHz–2690 MHz).

#### 1. INTRODUCTION

The fifth-generation mobile communication technology was deployed worldwide in 2019. The new technology provides superior performance compared to the ubiquitous 4G networks as it provides a throughput of 20 Gbps and latency of less than 5 ms. That will allow advanced IoT technologies such as autonomous vehicles and remote surgery to be more attainable in the near future. There are two kinds of 5G networks, mmWave and sub-6 GHz frequency bands. mmWave refers to the higher frequency bands ranging greater than 24 GHz, while the sub 6 GHz bands refer to lower than 6 GHz. The mmWave 5G networks are high-speed but also suffer from short-range networks; they are more suitable for urban areas with high population density or specific regions such as airports. On the contrary, sub-6 GHz 5G networks are slower than mmWave networks but have a more extended range and are more suited for rural and suburban regions.

Over the last decade, several designs of MIMO antennas operating in the sub-6-GHz for 5G have been proposed [1–11]. A 4 to 8 MIMO antenna system operating at sub-6 GHz 5G frequencies is sufficient for 5G mobile terminals. However, with the increase of processing capabilities of mobile terminals, the size of the antenna system is drastically squeezed [1,10]. That necessitates the need for advanced decoupling methods and feeding techniques. A good number of designs utilized the open-slot technique for operating frequency bands [4–9, 12, 13]. However, all reported open-slot designs utilize at least two layers of a printed circuit board (PCB); typically, the top layer is for the resonating open slot while the bottom layer is used for exciting the open slot elements. Others utilized a non-planar structure to enhance the resonance of the open-slot radiators as in [5]. While it is challenging to implement a

Received 14 February 2022, Accepted 11 May 2022, Scheduled 27 May 2022

<sup>\*</sup> Corresponding author: Mohamed M. Morsy (mmorsy@tamut.edu).

The author is with the Engineering and Physics Department, Texas A&M University Texarkana (TAMUT), Texarkana, TX 75503, USA.

decoupled miniaturized MIMO antenna system without using an isolation structure, some designs show sound isolation without the need for a complex isolation structure [9].

This paper proposes a novel design of the traditional open-slot radiators for the 5G MIMO applications in mobile terminals. In particular, the design represents  $4 \times 4$  MIMO elements printed on a single-sided FR4 material. The proposed design employs no isolation structure, so there is no tradeoff between having an isolation structure and the antenna's efficiency. The design consists of four open rectangular slots etched on the same side as the ground conductor and feeding striplines etched on the same layer. The size of the open slot and feeding striplines control the resonating frequencies. The performance of the antenna system is verified by both measurements and CST Studio 2021 simulation [14].

#### 2. ANTENNA DESIGN

Figure 1 shows the top view of the proposed antenna system. All elements are located at the four corners of the common ground plane. The total size of the antenna system, including the ground conductor, is  $L(100 \text{ mm}) \times W(40 \text{ mm})$ , which can easily fit in mobile terminals. The used substrate is a single-sided FR4 with  $\varepsilon_r = 4.3$ , loss tangent of 0.02, and thickness of 0.8 mm. Each antenna element consists of an L-shape feeding line and an open slot with a total size of  $L2(15 \text{ mm}) \times W2(12 \text{ mm})$ . The optimized dimensions of the vertical and horizontal traces of the stripline for each antenna are  $L1(9.5 \text{ mm}) \times 1 \text{ mm}$  and  $W1(9 \text{ mm}) \times 1.5 \text{ mm}$ , respectively. The gap between the L-shaped striplines and the ground conductor (S1) is 3 mm. Two rectangular slits are etched on the right and left sides of the ground plane to mitigate the mutual coupling effect. The size of the rectangular slits is  $Ls(20 \text{ mm}) \times Ws(3 \text{ mm})$ .



Figure 1. The layout of the proposed antenna system.

To gain more insight into the design principle, the current distribution at 2.6 GHz when port 1 is excited is shown in Fig. 2(a). The scale used for the current distribution density is 0-25 A/m. It is seen that the coupling between Ant 1 and the other three antenna elements is weak. The current flowing through element 1 (stripline and open slot at port 1) is almost confined to the area of the excited element. The weak current flow from port 1 to other antenna elements results in self-isolated antenna elements. Due to the symmetrical property of the design, other antenna elements have the same current distribution when being excited. Fig. 2(b) shows a photograph of the fabricated antenna.



Figure 2. (a) Surface current distribution (A/m) at 2.6 GHz, (b) photograph of the fabricated antenna.

#### 3. RESULTS AND PARAMETRIC ANALYSIS

To show the design principle of the proposed antenna system, a parametric analysis of the effect of varying L1 on the S-parameters is provided. The parametric study results are obtained while considering the entire antenna system, not just an isolated element. Fig. 3 shows the simulated S-parameters of Ant 1 while varying the length of L1. Due to the symmetry of the antenna systems, all elements have identical  $S_{11}$  values. It can be seen that tuning L1 contributes to achieving the required resonating band.



**Figure 3.** Simulated  $S_{11}$  of the antenna system as a function of L1.

Figure 4. Measured and simulated S-parameters of the proposed antenna system with L1 = 9.5.

Figure 4 shows the measured and simulated S-parameters of the proposed 4-element MIMO antenna system. Due to the symmetry of the designed antenna, all four elements have identical return loss, so only  $|S_{11}|$  is shown. Similarly, the mutual couplings between  $S_{21}$  and  $S_{43}$ ,  $S_{31}$  and  $S_{42}$ , and  $S_{32}$  and  $S_{41}$ 

are identical. Due to the symmetry, only necessary S-parameters are shown in Fig. 4. It can be seen that the isolation between Ant 1 and Ant 2  $(S_{21})$  has a maximum measured value of  $-11 \,\mathrm{dB}$ , while the measured isolations  $S_{31}$  and  $S_{41}$  are less than  $-18 \,\mathrm{dB}$ .

### 4. RADIATION AND MIMO PERFORMANCE

To evaluate the performance of the proposed MIMO antenna system, the envelope correlation coefficient (ECC) is analyzed. The analysis is done under the assumption. For accuracy, ECC values are obtained by the farfield radiation pattern equations in [15]:

$$\rho_{e} = \frac{\oint \left\{ \text{XPR} \cdot E_{\theta 1}\left(\Omega\right) E_{\theta 2}^{*}\left(\Omega\right) P_{\theta}\left(\Omega\right) + E_{\emptyset 1}\left(\Omega\right) E_{\emptyset 2}^{*}\left(\Omega\right) P_{\emptyset}\left(\Omega\right) \right\} d\Omega}{B1B2}$$

$$B1 = \sqrt{\oint \left\{ \text{XPR} \cdot E_{\theta 1}\left(\Omega\right) E_{\theta 1}^{*}\left(\Omega\right) P_{\theta}\left(\Omega\right) + E_{\emptyset 1}\left(\Omega\right) E_{\emptyset 1}^{*}\left(\Omega\right) P_{\emptyset}\left(\Omega\right) \right\} d\Omega},$$

$$B2 = \sqrt{\oint \left\{ \text{XPR} \cdot E_{\theta 2}\left(\Omega\right) E_{\theta 2}^{*}\left(\Omega\right) P_{\theta}\left(\Omega\right) + E_{\emptyset 2}\left(\Omega\right) E_{\emptyset 2}^{*}\left(\Omega\right) P_{\emptyset}\left(\Omega\right) \right\} d\Omega}$$

$$(1)$$

where XPR is the cross-polarization radiation. For simplicity, an isotropic environment, XPR = 1, is assumed.  $E_{\theta}(\Omega)$  and  $E_{\emptyset}(\Omega)$  are the orthogonal  $\theta$ - and  $\phi$ -components of the antenna radiation pattern.  $P_{\theta}(\Omega)$  and  $P_{\emptyset}(\Omega)$  are the angular power density functions of the incident wave. The calculated ECC values of the proposed MIMO antenna system are shown in Fig. 5. ECC 12 is the correlation coefficient between antennas 1 and 2. Similarly, ECC 13 and ECC 14 are the correlation coefficients between antennas 1,3, and 1,4. It can be seen that the calculated ECC values are well below 0.05 within the operating bandwidth.



**Figure 5.** Calculated envelope correlation coefficients (ECC) of the proposed antenna system.

Due to the symmetrical structure of the MIMO antenna system, the radiation patterns of only Antennas 1 and 3 at 2.6 GHz are shown in Fig. 6. All antenna elements have a maximum gain of 4.32 dBi at 2.6 GHz. We can also observe that the directions of maximum gains vary based on the antenna element's frequency and position.

The channel capacity loss (CCL) is also one of the crucial MIMO performance metrics. It indicates the multi-port transmission performance of the MIMO system without loss. The CLL of the proposed antenna is computed using the measured S-parameters [16].

$$CCL = -\log 2(\det(\alpha)),$$





Figure 6. Normalized radiation patterns at 2.6 GHz: (a) Ant. 1, (b) Ant. 3.

$$\alpha = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} \end{bmatrix}$$
(2)

and

The calculated CCL for the proposed antenna system is shown in Fig. 7. It is seen that the CCL values are less than the standard value of 0.4 bits/s/Hz [16] over the operating bandwidth. That makes it appropriate for a practical 5G MIMO system.

The mean effective gain (MEG) is another important diversity parameter of the MIMO antenna system. MEG is a measure of how the MIMO system performs in a fading medium and is defined as the ratio of the power received by the antenna under test to the power received by the anisotropic antenna in a fading environment. MEG values can be calculated using the measured s-parameters as shown in [17].

$$\text{MEG}_{i} = 0.5 \left( 1 - \sum_{j=1}^{N} |S_{ij}|^{2} \right),$$
(3)

where N is the number of antenna elements. To ensure an equal power ratio to each radiating element, the difference between MEG values should not be less than  $-3 \,\mathrm{dB}$  so that

$$|\mathrm{MEG}_i| - |\mathrm{MEG}_j| \le 3 \,\mathrm{dB}.\tag{4}$$

Morsy



Figure 7. Measured channel capacity loss (CCL) of the proposed MIMO antenna system.



**Figure 8.** Simulated mean effective gain (MEG) of the proposed MIMO antenna.



Figure 9. The radiation efficiency of the proposed antenna.

Table 1. Performance comparison between the proposed MIMO antenna and others.

Ref.	MIMO	Antenna	Bandwidth	Efficiency	ECC
	order	Dimensions	(GHz)	(%)	(dB)
[1]	4	$30.6 \times 30.6 \mathrm{mm^2}$	$3.3-4.2\mathrm{GHz}~(\mathrm{n77})$	47	< 0.48
		(low profile)			
[10]	4	$120 \times 50 \mathrm{mm^2}$	2.5–2.7 and 3.4–3.8	38-72	-
		(low profile)			
[18]	2	$60 \times 50 \times 28 \mathrm{mm}^3$	0.617–6	72	< 0.39
		(PIFA)			
[19]	4	$150 \times 73 \times 7 \mathrm{mm^3}$	3.4 - 3.6	55	< 0.1
[20]	4	$100 \times 55 \mathrm{mm^2}$	3.4 - 3.6	90	< 0.1
		(low profile)			< 0.1
Proposed	4	$70 \times 40 \mathrm{mm^2}$	2.43–2.7 (n38, n41)	94	< 0.05
antenna		(low profile)			< 0.05

#### Progress In Electromagnetics Research Letters, Vol. 104, 2022

Figure 8 shows the calculated MEG values of the proposed antenna system. It also shows that the maximum difference between MEG values is less than 1 dB over the operating bandwidth.

The radiation efficiency of the proposed MIMO antenna system is shown in Fig. 9. It can be observed that the radiation efficiency is about 94% in the operating frequency band.

Table 1 summarizes the essential characteristics of the proposed antenna system and other reported MIMO antennas. It can be seen that the proposed MIMO antenna system achieves a good balance of several design constraints such as efficiency, bandwidth, total size, and isolation.

# 5. CONCLUSION

A four-element MIMO antenna system for 5G applications has been presented. The proposed antenna system utilizes open slots and striplines for radiating elements. All elements are printed on a single-sided low-profile FR4 material. The antenna system covers 5G New Radio (NR) Frequency Bands n38 and n41 with minimum isolation of -11 dB. The proposed antenna shows a maximum realized gain and radiation efficiency of 4.3 dBi and 94%, respectively. The diversity performance of the proposed antenna is also considered. The envelope correlation coefficient (ECC) is less than 0.05, while the channel capacity loss (CCL) is measured to be less than 0.4 bits/s/Hz. The mean effective gain of antennas is also calculated. Measured, calculated, and simulated results show that the proposed antenna system is suitable for 5G applications.

## REFERENCES

- Chang, L. and H. Wang, "Miniaturized wideband four-antenna module based on dual-mode PIFA for 5G 4×4 MIMO applications," *IEEE Transactions on Antennas and Propagation*, Vol. 69, No. 9, 5297–5304, Sep. 2021.
- Zhao, A. and Z. Ren, "Wideband MIMO antenna systems based on coupled-loop antenna for 5G N77/N78/N79 applications in mobile terminals," *IEEE Access*, Vol. 7, 93761–93771, 2019, doi: 10.1109/ACCESS.2019.2913466.
- Sun, L., Y. Li, and Z. Zhang, "Wideband integrated quad-element MIMO antennas based on complementary antenna pairs for 5G smartphones," *IEEE Transactions on Antennas and Propagation*, Vol. 69, No. 8, 4466–4474, Aug. 2021, doi: 10.1109/TAP.2021.3060020.
- Ikram, M., N. Nguyen-Trong, and A. Abbosh, "Hybrid antenna using open-ended slot for integrated 4G/5G mobile application," *IEEE Antennas and Wireless Propagation Letters*, Vol. 19, No. 4, 710– 714, Apr. 2020, doi: 10.1109/LAWP.2020.2978181.
- Barani, I. R. R. and K.-L. Wong, "Integrated inverted-F and open-slot antennas in the metal-framed smartphone for 2 × 2 LTE LB and 4 × 4 LTE M/HB MIMO operations," *IEEE Transactions on Antennas and Propagation*, Vol. 66, No. 10, 5004–5012, Oct. 2018, doi: 10.1109/TAP.2018.2854191.
- Kumar, M. and V. Nath, "Open ended microstrip-line-fed compact wideband MIMO-diversity antenna with multiple asymmetric elliptical wide-slots," 2019 URSI Asia-Pacific Radio Science Conference (AP-RASC), 1–4, Mar. 2019, doi: 10.23919/URSIAP-RASC.2019.8738508.
- Barani, I. R. R., K.-L. Wong, Y.-X. Zhang, and W.-Y. Li, "Low-profile wideband conjoined open-slot antennas fed by grounded coplanar waveguides for 4 × 4 5G MIMO operation," *IEEE Transactions on Antennas and Propagation*, Vol. 68, No. 4, 2646–2657, Apr. 2020, doi: 10.1109/TAP.2019.2957967.
- Moat, T. E., S. I. Latif, and G. Lazarou, "Improving isolation of open multi-slot 4G antennas with microstrip feed line for MIMO applications," 2019 SoutheastCon, 1–2, Apr. 2019, doi: 10.1109/SoutheastCon42311.2019.9020338.
- Li, Y., C.-Y.-D. Sim, Y. Luo, and G. Yang, "High-isolation 3.5 GHz eight-antenna MIMO array using balanced open-slot antenna element for 5G smartphones," *IEEE Transactions on Antennas* and Propagation, Vol. 67, No. 6, 3820–3830, Jun. 2019, doi: 10.1109/TAP.2019.2902751.
- Dioum, I., K. Diallo, M. M. Khouma, I. Diop, L. Sane, and A. Ngom, "Miniature MIMO antennas for 5G mobile terminals," 2018 6th International Conference on Multimedia Computing and Systems (ICMCS), 1–6, May 2018, doi: 10.1109/ICMCS.2018.8525870.

- 11. Chattha, H. T., "4-port 2-element MIMO antenna for 5G portable applications," *IEEE Access*, Vol. 7, 96516–96520, 2019, doi: 10.1109/ACCESS.2019.2925351.
- Al Abbas, E., M. Ikram, and A. Abbosh, "Dual functional MIMO antenna system for mm-Wave 5G and 2 GHz 4G communications," 2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, 709–710, Jul. 2019, doi: 10.1109/APUSNCURSINRSM.2019.8888970.
- Karimian, R., H. Oraizi, S. Fakhte, and M. Farahani, "Novel F-shaped quad-band printed slot antenna for WLAN and WiMAX MIMO systems," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 405–408, 2013, doi: 10.1109/LAWP.2013.2252140.
- 14. "CST Studio Suite," Dassault Systèmes, 2021. www.cst.com (accessed Apr. 11, 2021).
- Stein, S., "On cross coupling in multiple-beam antennas," IRE Transactions on Antennas and Propagation, Vol. 10, No. 5, 548–557, Sep. 1962, doi: 10.1109/TAP.1962.1137917.
- Chae, S. H., S. Oh, and S.-O. Park, "Analysis of mutual coupling, correlations, and TARC in WiBro MIMO array antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 122–125, 2007, doi: 10.1109/LAWP.2007.893109.
- Rafique, U., S. Agarwal, N. Nauman, H. Khalil, and K. Ullah, "Inset-fed planar antenna array for dual-band 5G MIMO applications," *Progress In Electromagnetics Research C*, Vol. 112, 83–98, 2021.
- Yacoub, A., M. Khalifa, and D. N. Aloi, "Compact 2 × 2 automotive MIMO antenna systems for sub-6 GHz 5G and V2X communications," *Progress In Electromagnetics Research B*, Vol. 93, 23–46, 2021.
- Ren, Z., A. Zhao and S. Wu, "MIMO antenna with compact decoupled antenna pairs for 5G mobile terminals," *IEEE Antennas and Wireless Propagation Letters*, Vol. 18, No. 7, 1367–1371, Jul. 2019, doi: 10.1109/LAWP.2019.2916738.
- Ullah, R., S. Ullah, B. Kamal and R. Ullah, "A four-port multiple input multiple output (MIMO) antenna for future 5G smartphone applications," 2019 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 1-5, 2019, doi: 10.1109/ICECCE47252.2019.8940779.