A Highly Miniaturized Semi-Loop Meandered Dual-band MIMO Antenna System

 ISSN 1751-8644
 doi: 0000000000
 www.ietdl.org

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Abstract:

A novel dual-band 2-element directional multiple-input-multiple-output (MIMO) antenna system is presented with 68% miniaturization, which is achieved using a semi-loop meandered driven element and a small ground plane. The center frequency of operation is 2 GHz. The antenna system covers two bands: the Telemetry L-band 1.27–1.43 GHz, and the GSM/LTE band 1.8–2.133 GHz. The simulation and measurement results are in good agreement. **The proposed antenna system mimics the Quasi-Yagi antenna configuration** with a measured front-to-back ratio (FBR) of around 15 dB at 1.35 GHz and 17 dB at 2 GHz, which is achieved without using a large ground plane, extra metallic structures, multiple reflector elements or any complex technique. A gain of more than 5 dBi is measured for the single element with a total radiation efficiency of around 85% in both bands. The measured isolation of the proposed MIMO antenna is more than 15 dB with less than 0.0785 measured envelope correlation coefficient (ECC) values in both bands.

1 Introduction

Printed multi-band multiple-input-multiple-output (MIMO) antennas are an integral part of modern wireless devices because of their ability in helping to provide high data rates, better transmission quality, and reduce multipath fading effects in wireless channels. The channel capacity (data rates) increases with the increase in the number of independent MIMO channels [1]. **Making new compact and directional MIMO antenna systems is of high importance due to their low inter-element correlation in the far field.**

The operating principles of Yagi-Uda antenna were first presented in [2]–[3]. Yagi antennas are known for providing highly directional end-fire radiation patterns, high front-to-back ratios (FBR), and high gains [4]. Yagi antennas can be used in wide range of applications where high FBR and directivity is required, like in local positioning systems (LPS), radars, wireless access points, and in wireless sensor networks [4]. Quasi-Yagi antennas were first introduced in [5].

Many antenna miniaturization techniques can be found in literature like shorting posts or shorting walls [6], introducing slots [7], using metamaterials [8], material loading [9], and defected ground structures (DGS) [10]. However, most of these techniques are implemented on microstrip patch antennas or their derivations and only two Yagi-miniaturized designs [11]–[12] can be found in literature. The design presented in [11] has a gain of 4 dBi and FBR of greater than 6 dB covering the band from 2.3–2.69 GHz. It has a size of $65 \times 120 \times 130 \text{ mm}^3$. The design presented in [12] is based on Koch-fractal Yagi geometry at 431 MHz, where 24% miniaturization is achieved. It has a gain of around 5.7 dBi, FBR of 16.7 dB, and bandwidth of 9 MHz. The size of the antenna is around $214 \times 380 \times 203 \text{ mm}^3$. Both designs suffer from huge sizes, use large reflectors, and cover single narrow bands. For the first time, the design presented in [13] proposed a single element loop excited miniaturized Quasi-Yagi design targeting 2 GHz band. A miniaturization of 52% is achieved using a simple DGS. However, the proposed DGS affects the FBR performance and hence a moderate FBR of 8.5 dB is obtained. It has a gain of 4.23 dBi, efficiency of 92%, and minimum bandwidth of 620 MHz.

Quasi-Yagi antennas based on loop excitation with a small GND plane give omnidirectional patterns that are not of interest ($\text{FBR} \approx 1 \text{ dB}$). Several techniques were used in literature to achieve a directional radiation pattern with high FBR and minimum backward radiation. Electromagnetic bandgap structures (EBG) were used in [14] and [15] while soft isolated surfaces were used in [16] for microstrip patch antennas to achieve high FBR. [17] and [18] used inductor and resistor loading while [19] used rectangular microstrip ring antenna with coplanar waveguide (CPW)-feeding to eliminate the backward radiation. GND plane meandering and GND plane edge serration techniques were used in [20] and [21], respectively. Multiple reflectors on the same layer were used in [22] to achieve a FBR of around 13.4 dB, while the design presented in [23] used multiple 3D reflector layers to suppress the back-lobe radiation. Majority of the back-lobe reduction techniques mentioned above are complex, occupy large size, and are targeted for either microstrip or slot antennas and no such technique can be found for Quasi-Yagi antennas.

The work in [24] proposed for the first time, a dual wideband Quasi-Yagi MIMO antenna system with loop excitation targeting multiple standard bands. A large GND plane having the width of 38 mm was used in the design of a single element to achieve a measured FBR of 9.5 dB and gain of 5.98 dBi using a single director element. The size of the single element was $117.8 \times 78 \text{ mm}^2$. A recent single layer Yagi-like MIMO antenna system based on a semi-ring slot as its driven element appeared in [25] targeting the 3.6 GHz WiMAX band. A FBR of 10 dB was achieved by using a very simple slot reflector element. The size of the single element was $40 \times 40 \text{ mm}^2$ while its directivity was 6 dB without using any director element.

In this work, we present for the first time a highly miniaturized 2-element directional MIMO antenna system similar to a Quasi-Yagi antenna but with smaller spacings between the driven and director elements. A miniaturization factor of 68% (which is calculated from the difference between the areas of the single element of the proposed model and that of [24]) is achieved using simple loop meandering and a small GND plane having the width of only 19.1 mm which is almost half of the width of the GND plane used in [24]. To achieve highly directional end-fire radiation pattern with high FBR, a novel simple DGS structure with multiple slits is presented which switches

the main beam by 90° making it end-fire directional and further suppresses its back-lobe radiation to achieve high FBR of around 17 dB. The proposed antenna system is compact with single element size of $0.8\lambda_g \times 0.67\lambda_g$ and total board size of $1.6\lambda_g \times 0.67\lambda_g$ for the 2-element MIMO configuration.

The proposed antenna has a maximum measured gain of more than 5 dBi and 4.6 dBi for the single element and MIMO antenna system, respectively, using a single parasitic director element. While it has a measured total radiation efficiency of 85% and 78%, for the single and MIMO antenna system, respectively, in both bands. The proposed antenna system also shows good MIMO performance. It has at least 15 dB of port isolation which is achieved considering the close element spacing of $0.26\lambda_g$. It has less than 0.0785 of measured envelope correlation coefficient (ECC) values, diversity gain (DG) of 9.6 dB, and minimum multiplexing efficiency of 75% in both bands. So far, no printed directional MIMO miniaturized work has been reported based on loop excitation with such a small size.

The rest of the paper is organized as follows. Section II shows the detailed design procedure and parametric studies. Section III presents the results and discussions. Conclusions are given in Section IV.

2 Antenna Design Details

The antenna is designed using an $FR-4$ substrate with dielectric constant (ϵ_r) of 4.0, thickness of 0.76 mm, and loss tangent of 0.02. The proposed single antenna model is shown in Fig. 1(a). The length of the semi-loop meandered driven element is twice the guided wavelength $2\lambda_g$ (where λ_g is computed as: $\lambda_g = \lambda_0 / \sqrt{\epsilon_r}$) which is around 140 mm at the center frequency of 2 GHz. The diameter of the loop is 39 mm and its width is tuned to 1 mm. The overall size of the geometry is $60 \times 50 \text{ mm}^2$, while the size of the GND plane is $60 \times 19.1 \text{ mm}^2$. The driven semi-loop element is excited using simple microstrip line feeding below the substrate. The length of the transmission line is tuned to 15 mm while its width is set to 1.478 mm (50Ω) to get minimum reflection loss and match to 50Ω of the SMA connector. The distance between the driven element and the director/reflector (i.e. GND plane) is optimized with the objective of having higher gain/directivity and high FBR. This depends on the printed antenna type, geometry, and material used. Fig. 1 (b) shows the proposed MIMO antenna model. The distance between the two MIMO antennas is set to $0.26\lambda_g$ which corresponds to 20 mm at 2 GHz. The rest of the detailed dimensions are shown in Fig. 1. All dimensions are in mm.

3 Results and Discussion

3.1 Design Principles and Truncated GND Plane or Reflector Analysis

To optimize the dimensions of different parameters, most of the previous Yagi-Uda antennas used numerical techniques [2], [3], [5], [26], [27]. Loop antennas have several resonating modes like $0.5\lambda_g$, $1\lambda_g$, $1.5\lambda_g$, and $2\lambda_g$ [26]. Therefore, the length of the loop element is tuned accordingly to get resonance in the desired bands of operation. In our case, we have observed that the resonating mode for the semi-loop meandered driven element is close to $2\lambda_g$ at 2 GHz which corresponds to a length of 140 mm. The length of the reflector element is 60 mm while the length of the director element is tuned to 25 mm in accordance to [26]. This principle of designing printed Quasi-Yagi antennas is followed by the majority of works present in literature, e.g. [28]. The same principle can be applied to similar antenna geometries targeting other frequencies.

The size of the reflector and its spacing from the driven element has negligible effect on the forward gain but has significant effect on the FBR [26]. Therefore, to suppress the back-lobe radiation and to achieve high FBR, the truncated GND plane which acts as a reflector for Quasi-Yagi like antennas need to be carefully designed. Moreover, the size of the GND plane is also directly related to the overall size of the antenna system.

Fig. 1. Proposed antenna geometry models
a single antenna geometry
b MIMO antenna geometry

We start our analysis from the width of the GND plane. Initially, in order to achieve small overall size, we tuned the design with the width of the GND plane set to 7 mm. We then further carried our analysis on the GND plane and also observed its sensitivity on s-parameters as shown in Fig. 2(a). It can be observed that for the GND width of 7 mm, the antenna is multi-band with a minimum measured -6 dB bandwidth of 249 MHz (0.780-1.029 GHz) in the lower band and 286 MHz (1.932-2.218 GHz) in the upper band covering several LTE bands. However, when the width of the GND plane is increased by only 3 mm, the behavior is significantly changed and becomes stable afterwards. For this reason, throughout this work, a GND plane width of 19 mm was selected to allow enough GND plane for stable operation.

3.2 Defected GND Structure Analysis–Radiation Pattern Switching by 90°

To avoid using complex back-lobe suppression techniques like using EBG structures [14]–[15], isolation surfaces [16], resistors and inductors loading [17]–[18], multiple reflector elements on the same layer [22] or using additional metallic layers [23], one simple solution is to use a large GND plane as proposed in [24], where the width of the GND plane was tuned to 38 mm. But using large GND planes will eventually increase the overall size of the antenna system. On the other hand, in case of a smaller GND plane without DGS, the current density is maximum in a non-desired direction, i.e. the Y-Z plane which is orthogonal to the desired end-fire direction as shown in Fig. 2(b) without DGS case. However, by using the slit (S-1) in the GND plane exactly below the transmission line, the maxima of the current density is shifted to the X-Z plane as shown in Fig. 2(b) DGS case. Slit-2 (S-2) as shown in Fig. 1(a) is mainly responsible for the suppression of the back-lobe radiation after the pattern is shifted by 90° by slit-1 (S-1) towards the end-fire direction. The additional notches inside slit S-2 for the MIMO antenna system as shown in Fig. 1(b), are used to further reduce the back-lobe radiation using the same current density principle as shown in Fig. 2(b).

The above phenomenon is also verified by observing the 2D radiation patterns in both azimuth and elevation planes for three different

Fig. 2. GND plane analysis

a S-parameter curves for different GND plane widths

b Current distribution at 2 GHz: without DGS, with DGS

c 2D radiation patterns (azimuth cut at $\theta = 90^\circ$) at 2 GHz for three different cases

d 2D radiation patterns (elevation cut at $\phi = 0^\circ$) at 2 GHz for three different cases

cases: GND plane width of 38 mm without DGS, GND plane width of 19.1 mm without DGS, and GND plane width of 19.1 mm with DGS as shown in Fig. 2(c and d). It can be noticed that for a small GND plane having a width of 19.1 mm without DGS case, the radiation pattern is omnidirectional along Y-Z plane as shown in both azimuth and elevation planes. However, the radiation pattern is shifted by 90° and the desired directional end-fire radiation pattern is obtained by either using a large GND plane having a width of 38 mm or by using half a GND plane having a width of 19.1 mm with DGS. Also it can be observed that the proposed DGS shows even better performance (8 dB greater FBR) over the large GND plane in terms of FBR.

3.3 Single Antenna Element Results

The single antenna element shown in Fig. 1 was modeled and simulated in CST^{TM} including the SMA connector model. Metal parts were modeled with copper material properties to have better match with the actual fabricated prototype (as compared to using PEC). The prototype was fabricated at the Antennas and Microwave Structure Design Laboratory (AMSDL-KFUPM) using a Protomat-S103 (LPKF) milling machine. An Agilent N9918A vector network analyzer (VNA) was used to measure the S-parameters. Fig. 3(a) shows the simulated and measured s-parameter curves, while the inset figure shows the fabricated prototype of the single element. It has a minimum return loss of 23 dB, measured -6 dB bandwidth of 190 MHz (1.29-1.48 GHz) in the lower band, and measured bandwidth of 196 MHz (1.904-2.1 GHz) in the upper band. A good agreement between the simulated and measured results is observed.

The antenna radiation characteristics were measured in a Satimo Star-Lab chamber at KAUST-KSA. Fig. 3(b) shows the single element measured and simulated gain and efficiency curves. The inset shows the measurement setup inside the chamber. It can be seen that the maximum measured gain is more than 5 dBi in both bands, while the minimum measured total radiation efficiency is around 90%. A good agreement is found between the measured and simulated results

with slight differences, which are attributed to the losses (cable and connector) and non-idealities of material properties.

Sensitivity analysis were performed on various design parameters and it was noticed that some of the parameters were very sensitive in determining the performance in terms of gain, efficiency, and FBR. Table 1 summarizes the effect of the length and spacing of the director element from the driven loop element on the gain of the antenna. It can be seen that by increasing the length of the director until 25 mm, the gain significantly increases while it starts decreasing afterwards. Similarly, the gain of the antenna increases by increasing the spacing until 1.6 mm and starts decreasing afterwards. Therefore, the length of the director element is tuned to 25 mm and its spacing is optimized to 1.6 mm.

Table 2 summarizes the effect of spacing between the driven loop element and GND plane (reflector), and spacing between the meandered arms of the loop element on the efficiency of the antenna. It can be observed that the efficiency of the antenna is very sensitive to these parameters. The efficiency increases with an increase in the spacing between the driven element and the GND plane until 1.9 mm, after that it starts decreasing. Moreover, the efficiency increases to 94% by increasing the spacing between the arms of the loop element until 0.5 mm and it is significantly decreased when the spacing is further increased.

Table 3 shows the effect of the width and depth of S-2 on the FBR. It can be observed that by increasing the width and depth of S-2 increases the FBR by around 17 dB and hence its values were set to 5.9 mm and 6.8 mm for the width and depth, respectively. Fig. 3 (c) and (d) show the normalized measured 2D radiation patterns of the proposed single antenna element in both azimuth and elevation planes at 2 GHz. Fig. 3(c) shows the 2D pattern in azimuth plane (phi-cut) obtained at $\theta = 90^\circ$, while Fig. 3(d) shows the pattern in elevation plane (theta-cut) obtained at $\phi = 0^\circ$. It can be seen from both azimuth and elevation planes that the proposed antenna has a minimum measured FBR of 17 dB which ensures very good directional performance.

Fig. 3. Single element simulated and measured results
a S-parameter curves (inset shows the fabricated prototype of the single element)
b Gain and efficiency curves (inset shows the measurement setup inside the chamber)
c Normalized radiation patterns (azimuth cut at $\theta = 90^\circ$) in terms of E_{Total} (dB) at 2 GHz
d Normalized radiation patterns (elevation cut at $\phi - max = 6^\circ$) in terms of E_{Total} (dB) at 2 GHz

Table 1 Effect of length and spacing of the director element from the driven element on gain of the antenna

Length (mm)	Gain (dBi)	Spacing (mm)	Gain (dBi)
18	3.4	0.3	2.34
20	4.38	0.6	2.97
22	4.98	0.9	4.2
24	5.23	1.2	4.678
25	5.98	1.5	5.4
27	4.68	1.6	5.97
30	2.91	1.9	3.43

Table 2 Effect of the loop-GND spacing and spacing between the loop arms on the efficiency of the antenna

Loop-GND spacing (mm)	Efficiency (%)	Loop-Arms Spacing (mm)	Efficiency (%)
0.4	52	0.2	43
0.8	58.76	0.4	68
1.2	69.9	0.5	94
1.5	87.2	0.6	71.23
1.9	93.8	0.8	82
2	81	1	62.45
2.4	62	1.2	54.67

Table 3 Effect of the width and depth of slit-2 (S-2) on FBR

S-2 Width (mm)	FBR (dB)	S-2 depth (mm)	FBR (dB)
1.5	4	2	3.69
3	7.92	3	4.98
4	9	4	6.51
5.5	13.3	6	12.57
5.9	21	6.5	20.61
6.2	16	6.8	21
8	10	7.3	17

3.4 MIMO Antenna System Results

The simulated and measured s-parameter curves for the MIMO antenna system are shown in Fig. 4(a). The fabricated prototype of the MIMO antenna system is shown in the figure inset. It is observed that this MIMO antenna system has a minimum measured -6 dB bandwidth of 160 MHz, from 1.27-1.43 GHz in the lower band, and minimum measured bandwidth of 333 MHz from 1.8-2.133 GHz in the upper band. The measured isolation is atleast 15 dB within both bands even by considering small inter-element spacing of $0.26\lambda_g$ which ensures good port efficiency performance. The spacing between

Fig. 4. Simulated and measured MIMO antenna system results
a S-parameter curves (inset shows the fabricated prototype of the MIMO antenna system)
b MIMO measurement setup inside the chamber
c Ant-1 gain and efficiency curves
d Ant-2 gain and efficiency curves

MIMO elements is usually optimized and it varies from application to application [1]. Good agreement is observed between the simulated and measured results. Fig. 4(b) shows the MIMO antenna setup inside the chamber.

Fig. 4(c) and (d) show the simulated and measured maximum gain and total radiation efficiency curves of the MIMO antenna system. It can be observed that the gain is 4.6 dBi while the measured efficiency is around 78% in both bands. Simulated and measurement results are in good agreement.

The normalized measured and simulated 2D radiation patterns of the MIMO antenna system in terms of E_{Total} at 1.35 GHz are shown by both ϕ and θ planes of Fig. 5. Fig. 5 (a) and (b) shows these patterns obtained at $\theta = 90^\circ$ (azimuth cut) for element 1 and 2, respectively. It can be observed that the field for element 1 and 2 is maximum at $\phi = 42^\circ$ and $\phi = 330^\circ$ respectively, and are apart from each other by 72° . Fig. 5(c) and (d) shows the patterns obtained at $\phi_{max} = 42^\circ$ (elevation cut) and $\phi_{max} = 30^\circ$ for element 1 and 2, respectively. Similarly, Fig. 6 shows the normalized simulated and measured patterns at 2 GHz. Fig. 6 (a) and (b) shows the measured and simulated patterns obtained at $\theta = 90^\circ$ for element 1 and 2, respectively. It can be observed that the field for element 1 and 2 is maximum at $\phi = 43^\circ$ and $\phi = 328^\circ$ respectively, and are apart from each other by 75° . Fig. 6(c) and (d) shows these patterns obtained at $\phi_{max} = 43^\circ$ and $\phi_{max} = 32^\circ$ for element 1 and 2, respectively. As evident from both figures, the patterns are completely tilted in both ϕ and θ planes which ensures that the MIMO channels are highly uncorrelated. In both planes, simulation and measurement results are in close agreement. The obtained FBR in both planes (Fig. 5 and Fig. 6) is above 15 dB.

Table IV summarizes the comparison of different parameter results of both the single element and the MIMO antenna system of this work to other works in literature. It can be seen that the proposed MIMO antenna system is the first miniaturized printed loop excited directional MIMO work. Moreover, both single and MIMO antenna systems use a loop as a driven element and are compact in size by covering dual low frequency bands with high efficiency values. The proposed design is similar to a Quasi-Yagi antenna configuration and ensures good Yagi performance in terms of FBR and gain as compared to other works.

Using the measured S-parameters, TARC curves [1] are calculated as shown in Fig. 7(a). A stable response is observed irrespective of the phase variation between the two ports.

For diversity performance evaluation, the 3D radiation patterns are used to find the ECC values using (1). Simulated and measured ECC curves (evaluated at specific frequency points within the band) are shown in Fig. 7(b). It is observed that the measured ECC reaches to the maximum value of 0.0785 (in both bands), which indicates that the radiation patterns are not correlated (the tilts are obvious from Fig. 5 and Fig. 6). The average diversity gain (DG) computed from ECC values according to [29] is 9.6 dB which is very close to the maximum value of 10 dB. The multiplexing efficiency calculated from the measured ECC and total efficiencies of the individual antennas according to [30] is 75%. Hence, the proposed MIMO antenna system ensures good MIMO performance in terms of isolation, correlation, TARC, DG, and Multiplexing efficiency.

$$\rho_e = \frac{|\iint_0^{4\pi} [\vec{F}_1(\theta, \phi) \times \vec{F}_2(\theta, \phi)] d\Omega|^2}{\iint_0^{4\pi} |\vec{F}_1(\theta, \phi)|^2 d\Omega \iint_0^{4\pi} |\vec{F}_2(\theta, \phi)|^2 d\Omega} \quad (1)$$

Fig. 5. Normalized measured and simulated 2D radiation patterns in terms of E_{Total} (in dB) at 1.35 GHz
a azimuth cut at $\theta = 90^\circ$, element 1
b azimuth cut at $\theta = 90^\circ$, element 2
c elevation cut at $\phi_{max} = 42^\circ$, element 1
d elevation cut at $\phi_{max} = 30^\circ$, element 2

Fig. 6. Normalized measured and simulated 2D radiation patterns in terms of E_{Total} (in dB) at 2 GHz
a azimuth cut at $\theta = 90^\circ$, element 1
b azimuth cut at $\theta = 90^\circ$, element 2
c elevation cut at $\phi_{max} = 43^\circ$, element 1
d elevation cut at $\phi_{max} = 32^\circ$, element 2

Table 4 Comparison of different antenna parameters to other related designs

Parameters	Single Element					MIMO		
	[11]	[12]	[13]	[24]	This Work	[24]	[25]	This Work
Driven Element	Monopole	Dipole	Loop	Loop	Loop	Loop	Magnetic-Dipole	Loop
Freq (GHz)	2.4	0.431	2, 4.2	2, 4.2	1.4, 2	2, 4.2	3.6	1.4, 2
Size (mm ²)/(mm ³)	65 × 120 × 130	214 × 380 × 203	55 × 80	118 × 78	60 × 50	263 × 263	80 × 40	120 × 50
FBR (dB)	6-meas	16.7-sim	8.5-sim	9.5-meas	17-meas	13.8-meas	10-meas	17-meas
Gain (dBi)	4-sim	5.7-sim	4.23-sim	5.98-meas	5-meas	5.8-meas	4.3-meas	5-meas
Efficiency (η%)	—	86-sim	92-sim	65-meas	85-meas	65-meas	73-meas	78-meas
Miniaturization	Yes	Yes, 24%	Yes, 52%	No	Yes, 68%	No	No	Yes, 68%

Fig. 7. Simulated and measured TARC and ECC curves for MIMO antenna system
a TARC curves
b ECC curves

4 Conclusions

In this paper, a highly miniaturized dual wideband directional MIMO antenna system is presented that mimics the features of the Quasi-Yagi antenna. A miniaturization of 68% is achieved by using semi-loop meandering and small GND plane structure. Both single element and MIMO antennas are compact in size as compared to other single or MIMO Quasi-Yagi designs. The proposed antenna system has a very high measured FBR of 17 dB at 2 GHz with a small GND plane width of 19.1 mm. The omnidirectional pattern is shifted by 90° towards the desired end-fire direction and the back-lobe radiation is reduced by using a very simple DGS, unlike complex back-lobe reduction techniques present in the literature. The proposed design has a maximum measured gain of more than 5 dBi and 4.6 dBi for the single element and MIMO antenna system, respectively. It has a measured total radiation efficiency of around 85% and 78% for both single and MIMO antennas. The proposed antenna system also ensures good MIMO performance in terms of isolation, ECC, TARC, DG, and multiplexing efficiency.

5 Acknowledgment

The authors would like to acknowledge the support provided by the Deanship of Scientific Research (DSR) at KFUPM under Project No. KAUST 002.

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