Smartphone metal-casing integrated frequency-reconfigurable multiple-input multiple-output slot antenna

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Abstract
A novel four-element frequency-reconfigurable multiple-input multiple-output (MIMO) slot antenna for a smartphone with metal-casing is presented. The inherent disadvantage of ultra-narrow bandwidth of thin slots is overcome with the help of frequency reconfiguration using varactor diodes. Antenna operation within the frequency range of 5.1–6 GHz was achieved. MIMO performance, smartphone components, and user effects were investigated. Simulated and experimental results demonstrate excellent performance.

KEYWORDS
frequency-reconfigurable antenna, metal casing, MIMO, slot antenna, varactor diode

1 INTRODUCTION

Smartphones with metal-casings have become widely available and popular. Phones with metal casings bring significant challenges in terms of antenna design because performance of commonly used antennas like planar inverted-F antennas (PIFAs),¹ monopoles,² loops,³ and inverted-F antennas (IFAs), and so on suffers from serious degradation in the presence of other objects nearby, especially if the other object is metal. For these electric-type antennas, the impedance matching, bandwidth, and radiation efficiency suffer significantly from the deleterious effects of the image currents caused by the metal chassis. In contrast, magnetic type antennas such as slots are generally more compatible with metallic objects where they do not require non-metal region (keep-out area) for antenna placement and have equivalent radiation characteristics as traditional antennas. Recently, some antennas integrated with metal-casings have been reported in the literature.⁴–⁸

Also, the advent of 5G communications have created a significant need for reliable and high-speed systems which ushered in multiple-input multiple-output (MIMO) antennas⁹–¹² with reconfigurable capabilities as a new class of promising antennas because of the high capacity and unprecedented performance flexibility they provide. Legitimately, MIMO antennas are being designed, developed and adopted for many applications such as wireless local area network (WLAN), long-term evolution (LTE), internet of things (IoT), and future 5G networks. The 5–6 GHz frequency range is of tremendous interest because of a proliferation of applications it can support. Slot antennas if designed for a metal-frame smart phone in this frequency range will enable multiple antennas to allow MIMO array performance. However, if such slots are placed on the thinner edge of a device, they will inherently be very narrow-band because of their slender width (1–2 mm). This creates a considerable challenge in terms of operational bandwidth. This technical barrier with narrow bandwidth can be addressed with the help of frequency reconfiguration.¹³
Frequency reconfiguration of slot antennas have been reported in the literature some with the help of PIN diodes,\textsuperscript{14,15} some using RF MEMS,\textsuperscript{16,17} and some using varactor diodes.\textsuperscript{18–22} Reconfiguration using varactor diodes provides smooth frequency tuning by varying the varactor capacitance.

In this article, we introduce a new varactor diode reconfigurable slot antenna for metal chassis-based smartphone applications. Since the slot element is very slender and it can be easily placed on the thin edge of a device. The function of frequency reconfiguration allows this antenna to operate from nearly the entire frequency range of 5–6 GHz, which is impossible to achieve with a non-reconfigurable thin slot antenna. Earlier, our group reported an edged-mounted pattern reconfigurable (PIN diode) collinear dipole antenna array for a device with plastic housing.\textsuperscript{11} The present work focuses on a new class of frequency reconfigurable slot antenna that can also be arranged in a collinear array form to facilitate MIMO applications. Although we choose our analysis frequency to be the 5–6 GHz frequency range the concept developed can be adapted for application at other frequencies, for example, 3–4 GHz or higher.

Although some articles have been published on frequency-reconfigurable slots using varactors\textsuperscript{18–22} while other studies present slot antennas designed on handset metal-casing,\textsuperscript{5–8} this is the first ever reported work on frequency-tuning collinear MIMO slot array for smartphone application. One of the features that distinguishes this work is that the antenna elements are designed on the handset rim (or frame) that saves space and allows a large LCD panel to be disposed off on the smartphone with negligible effect on the antenna performance.

This article is organized as follows. Section 2 presents the antenna configuration and simulation results. The fabricated antenna and measured results are discussed in section 3. Section 4 introduces the performance evaluation including MIMO performance and the effect of the large handset metallic components such as battery and an LCD. The conclusions of this work are summarized in section 5.

## 2 | SLOT MIMO ARRAY STRUCTURE AND SIMULATIONS

### 2.1 | Slot array in free space

To take full advantage of MIMO operation, four thin (1 mm slot width) slot elements were considered on a slender metal-frame device with 140 mm length, 70 mm width, and 6 mm thickness (Figure 1). Each slot is excited off-center using a 50-Ω source and can be reconfigured in frequency using an integrated varactor diode. The varactor diode location was carefully selected based on the voltage and current distributions on the slot. There is a trade-off between the varactor tuning range and the slot impedance matching. Moving the varactor closer to the feed deteriorates the impedance matching while moving it closer to the slot edge reduces the tuning range. Using HFSS parametric study, the optimum location of the varactor was determined to achieve the highest tuning range with the best impedance matching.

To understand the effects of dielectric loss, a free-space scenario is analyzed first consisting of slots created directly on the metal frame that are approximately half-wavelength long at 6.0 GHz. Since the slots are arranged in a collinear arrangement a smaller edge-to-edge spacing (S) of about 0.25λ at 6.0 GHz is considered reasonable\textsuperscript{10} which would ensure low mutual coupling between the adjacent elements\textsuperscript{23–26}

Initial simulations were performed by modeling the varactors as capacitors with values varying as 0.1, 0.28, 0.38, and 0.45 pF. The frequency reconfiguration capability of this antenna is evident from the S\textsubscript{nn}-parameter results shown in Figure 2A. The antenna operating frequency is reconfigured as 5.2, 5.4, 5.6, and 5.8 GHz as the varactor capacitance changes. Port-to-port isolation results shown in Figure 2B–D demonstrate that isolation exceeds 15 dB for all cases.

### 2.2 | Slot array on FR4

To facilitate experimental fabrication and testing of the antennas, we decided to use a 0.8-mm thick FR4
substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$). The idea was to place the FR4 substrate on one of the device edges as shown in Figure 3 where the slots are etched on the top metal ground plane while the substrate side resides underneath it. An L-shaped microstrip feedline is then used to excite each slot. The location and placement of the varactors, the DC bias traces, and the other components can be seen from Figure 3.

Because of the FR4 substrate the slot length (24 mm) in free space had to be reduced to 18 mm to maintain the same operating frequency. The reduction in the slot length allowed $S$ to increase from 12 mm to 17 mm that further improve the isolation between the ports.

Two varactor diodes and their DC biasing circuit (Figures 3 and 4B) were placed on the back side of the slot. Two shorting pins were employed to connect the varactors to the slot. The MACOM varactor diode MGV 125-20-0805 was selected because it can provide low capacitance values from 0.1 pF to 1.0 pF. The varactor tuning voltage is from 0 to 22 V with the tuning ratio is up to 10. Figure 4A shows the equivalent RLC series circuit for the varactor, according to its data sheet, that was used to model the varactor diode in simulations.

Before fabrication, the proposed MIMO slot antennas were modeled and simulated as function of variable capacitance, first considering zero varactor resistance. The simulated $S$-parameters data of the slot array on FR4 PCB as function of frequency are shown in Figure 5. As all slots have identical geometry, some $S$-parameters provide identical curves. Figure 5A shows the magnitude of the reflection coefficients which indicate that the resonance frequencies are smoothly shifted over the frequency band from 5.11 to 5.99 GHz, that is, 16%, for $S_{ii}$ ($i = 1, 2, 3, 4$) $< -10$ dB. The frequency tuning
is achieved for capacitance values from 0.11 to 0.24 pF. The simulated coupling curves are shown in Figure 6B–D, which show that the isolation is more than 20 dB over the different bands of interest. The isolation improvement compared to the free-space design (see Figure 2) is because of the increase of the spacing (S) between the slots.
The simulated total efficiencies of the slot antenna elements at different frequencies can be seen from Table 1. The radiation efficiencies were calculated in the receive mode where all ports were excited. Efficiency exceeds 90% for the free-space case (no FR4, zero varactor resistance). The use of the FR4 substrate causes 10%–15% efficiency degradation while including a loss resistance (3.2-Ω) in the varactor diode simulation model causes another 12%–15% efficiency degradation. Nonetheless, considering FR4 loss and varactor resistive loss the total efficiency is still between 51% and 78%. Efficiency can be improved further by considering alternative approaches such as the use of a digitally tuned capacitor (DTC) that has low parasitic loss and internal resistance, and can be programmed. Another option would be to switch a set of fixed capacitors, which are used in many adaptive matching circuits in new commercial devices.

Simulated realized gain radiation patterns computed at 5.4 GHz for one of the four antennas (the FR4 model) are plotted in Figure 6. The definitions of the planes, for example, XZ, YZ, ZY, and so on with respect to the device and slot geometries can be seen from Figure 1. Since the patterns of each antenna element are essentially similar only one set is presented. The two elevation plane patterns (XZ-plane in Figure 6A and YZ-plane in Figure 6B) resemble the pattern of a resonant half-wavelength long dipole or resonant slot. There is some cross polarization (Gθ) in the XZ-plane pattern because of the presence of the metal chassis in that plane. The Gθ component is thus believed to be because of currents flowing on the metal chassis. The azimuthal plane (XY-plane) pattern in Figure 6C shows between 0 and 5 dBi realized gain at most angles except within about a total 110° region.

Simulated surface current and electric field distributions at 5.4 GHz (C = 0.2 pF) are shown in Figure 7. As noted, when all ports are excited, the currents and fields are mostly localized around the slots. Hence, the effect on the antenna pattern due to the presence of the metal casing is expected to be limited (Figure 6), unlike other antennas such as monopoles, PIFAs or IFAs where the
effects of the ground plane on antenna patterns are more pronounced.\textsuperscript{1,2} The surface current distributions and the electric fields in Figure 7 also illustrate that there is negligible interaction or coupling between the slot elements.

3 EXPERIMENTAL FABRICATION AND MEASURED RESULTS

The four-slot reconfigurable MIMO antenna (photograph shown in Figure 8) was fabricated and measured. As mentioned before, the slots were etched on a 0.8 mm thick FR4 substrate (Figure 8A,B). Each slot was fed using a 50-Ω SMA connector. Photographs of the slot-side are shown in Figure 8A while those of the varactor-side including their bias traces are shown in Figure 8B. The varactors were controlled using a variable DC supply. The FR4 substrate containing the slots and the varactors were placed on the edge of a 140 mm long metal casing made using copper tape (to mimic a metal frame phone chassis) as shown in Figure 8C.

Antenna S-parameters were measured for varactor DC bias voltages of 6.2, 6.9, 7.7, and 8.8 V, representing corresponding varactor capacitances of 0.24, 0.20, 0.16, and 0.11 pF, respectively. Measured S-parameter results for these cases are plotted in Figure 9.

Measured $S_{mm}$ results, shown in Figure 9A, indicate that with decreasing capacitance, antenna resonant frequency shifts to higher frequencies as expected from simulation observations (Figure 5). For the four capacitance values, the experimental reconfiguration frequencies are 5.2, 5.4, 5.6, and 5.8 GHz, respectively like the simulated ones. The overall frequency reconfiguration range (approximately 5.1–5.9 GHz) for the experimental case is

![Photographs of the fabricated multiple-input multiple-output (MIMO) antenna (A) slot array side (B) feeding and biasing circuits side (C) slot MIMO array integrated with smartphone metal casing prototype](image)

![Graphs showing measured S-parameters of the four-element slot reconfigurable antenna for different varactor capacitances (A) $S_{mn}$ and (B) $S_{mm}$](image)
about 100 MHz smaller than the simulated frequency reconfiguration range (approximately 5.1–6 GHz). The slight difference between the simulated and measured responses could be attributed to the combined effects from the DC biasing wires, the SMA connectors, and the slightly non-uniform surface of the metal casing for the experimental case. Measured mutual coupling ($S_{mn}$) results for the same varactor capacitance values can be seen from Figure 9B–D which clearly show that the isolation between the antenna elements is greater than 30 dB within the frequency band above.

The antenna pattern, efficiency, and gain were measured in an anechoic chamber. The measurement setup is shown in Figure 10A. As seen, a variable DC power source was used to bias the varactors through biasing wires. During measurement, the prototype was placed on lossless foam while the DC source was surrounded by lossy foam to shield it and avoid any reflections or additive noise. The simulated and measured azimuth plane ($\theta = 90^\circ$) gain patterns of the proposed antenna at the resonance frequencies for different varactor capacitance values are compared in Figure 10. As noted, there is a good agreement between the simulated and measured radiation patterns at the studied frequencies. Generally, the pattern peak points at around 150° in the azimuth plane. Further, the simulated and measured total efficiency for different varactor capacitances are shown in Figure 11. As seen, both simulation and measurement results indicate that with decreasing capacitance values, the peak of the efficiency shifts to higher frequencies following the frequency tuning. However, the measured efficiency is less than the simulated most likely due to the presence of the DC bias wires, power supply, the wood platform, the cables, and connectors, etc. which were not included in the simulation models. Nevertheless, as discussed before, efficiency can be improved by using low-loss substrate and alternative approaches such as DTC to provide better efficiency response.

The simulated and measured peak realized gain for different values of the varactor capacitance are compared Figure 12. It indicates that the peak gain shifts to higher frequencies with the decrease of the varactor capacitance.
Simulations show that the slot elements can maintain gain of around 5-dB over the operating bandwidth by varying the varactor capacitance. However, measured gain results show slightly higher peak gain compared to simulations.

4 | THE FOUR-SLOT ANTENNA IN MIMO CONFIGURATION

The performance of the proposed four-slot frequency reconfigurable antenna was evaluated in a MIMO
configuration. To facilitate that the envelope correlation coefficient (ECC) data were calculated using the radiation patterns for the four varactor capacitance values. ECC results shown in Figure 13 illustrate that ECC <0.05 over the frequency band of 5.1–6 GHz.

The cumulative density function (CDF) and the ergodic MIMO capacity (bps/Hz) were also computed using formulations available in Reference 27 with the results being shown in Figure 14. For comparison, the CDF corresponding to the reference Rayleigh distribution and single-input single-output (SISO) case is also plotted. It is clear that the proposed antenna configuration provides improved CDF performance as well as higher capacity compared to the reference case. From the reconfiguration point of view, both CDF and capacity improve with decreasing varactor capacitance. This occurs because antenna efficiency improves with decreasing varactor capacitance for the latter (see Table 1).

5 EFFECT ON ANTENNA DUE TO THE PRESENCE OF OTHER COMPONENTS

Modern smart phones contain various different components on the printed circuit board and within the device chassis to allow functions like voice calls, messaging, photography, web browsing, video, and so on. The effects of such components on antenna performance is quite challenging to evaluate because of variability in device structures, materials and sizes for those components. Nonetheless, studies can be conducted considering some generic building blocks for the most common and large components, for example, the battery and the LCD. Such a study could lead to better insight for future designs. Therefore, the effects of a battery and an LCD on the performance of the proposed antenna was studied using HFSS. A battery and an LCD were modeled as metal boxes with dimensions of 70 × 50 × 4 mm³ and 130 × 60 × 0.1 mm³, respectively (Figure 15).

Simulated S-parameters (not shown for brevity) demonstrated the same reconfiguration frequencies within $|S_{nn}| \leq -10$ dB as reported before. Port-to-port isolation between the antenna elements degraded somewhat but isolation was still greater than 15 dB for all cases.

Simulated radiation patterns (total realized gain) showed stable patterns over the 5.1–6 GHz frequency band. Realized gain patterns at 5.4 GHz for $C = 0.2$ pF are shown in Figure 16. The elevation-plane patterns ($\phi = 0^\circ$ and $\phi = 90^\circ$) in general resemble the pattern of a half-wave dipole antenna. Patterns of slots 1 and 2 are the least affected while the patterns of slots 3 and 4 are the most affected due to the battery and the LCD. This is expected however because slots 3 and 4 are directly adjacent to the battery. The patterns on the $\phi = 90^\circ$ plane for slots 3 and 4 suffer more distortions than the patterns on the $\phi = 0^\circ$ plane. The patterns on the azimuthal plane ($\theta = 90^\circ$) experience minimal degradation.

Simulated efficiencies for the case with the battery and the LCD (Case I) are listed in Table 2. For comparison, the efficiency data for the antenna without the battery and the LCD (Case II) are also listed in the parenthesis. Efficiency results for Case I at 5.6 and 5.8 GHz are similar to those for Case II. Efficiency for Case I decreases between 5% and 14% compared to Case II.
II as the operating frequency increases i.e. if varactor capacitance increases.

6 | USER EFFECT

The effect of user’s hand on the performance of the proposed slot antenna was investigated for two standard hand grips: single-hand grip for talk or data mode and two-hand grip for browse mode. Figure 17 depicts the two studied grip positions. The hands were modeled with the standard human’s hand phantoms available within Ansys HFSS libraries. The reflection coefficients of antenna elements at different varactor capacitance values for the studied models are shown in Figure 18. As noted, the effect of hands on the reflection coefficient is quite minimal for both models, and the antenna exhibits good frequency tuning over the band of interest when operate close to hands without any need for adaptive impedance matching networks.

Generally, the user’s hands degrade the antenna radiation efficiency due to the lossy nature of human tissues, which absorb a considerable amount of power. The efficiency of slot elements was studied for the hand models. As expected, the antenna efficiency is deteriorated. However, in the two-hand model, the efficiency reduction is less than the single-hand model as the fingers are not very close to the slots. The efficiency is reduced by about 33% for single-hand model compared to free-space case while it is reduced by 21% for the two-hand model. Since mismatch loss is almost negligible, the efficiency reduction is attributed to the radiation efficiency deterioration. However, it is important to note that the antenna efficiency depends on the size of hand, the spacing between the hand with respect to the device, and the way how the device is hold. Hence, the efficiency can be improved depending on these circumstances.

Specific absorption rate (SAR) was also studied to characterize the impact of the proposed MIMO antenna radiation on human head. The SAR calculation was estimated using Ansys HFSS for the head model as shown in Figure 19. To mimic the practical scenarios in simulation, the spacing between the mobile and ear is 1 mm and between the mobile and

| Varactor capacitance | \( C = 0.11 \) pF | \( C = 0.16 \) pF | \( C = 0.20 \) pF | \( C = 0.24 \) pF |
|----------------------|-----------------|-----------------|-----------------|-----------------|
| Frequency            | 5.8 GHz         | 5.6 GHz         | 5.4 GHz         | 5.2 GHz         |
| Efficiency (%)       |                 |                 |                 |                 |
| Port 1               | 79 (78)         | 73 (72)         | 58 (63)         | 39 (51)         |
| Port 2               | 78 (78)         | 72 (72)         | 57 (63)         | 38 (51)         |
| Port 3               | 78 (78)         | 66 (72)         | 55 (63)         | 38 (51)         |
| Port 4               | 80 (78)         | 70 (72)         | 56 (63)         | 37 (51)         |
**Figure 17**  Studied hand grip positions (A) single-hand voice/data model (B) two-hand browse model

**Figure 18**  Simulated reflection coefficients for the hand models (A) single-hand voice/data model (B) two-hand browse model

**Figure 19**  (A) Specific absorption rate (SAR) Simulation model (B) average SAR distribution at 5.8 GHz

**Table 3**  Calculated SAR values for different varactor capacitances

| Varactor capacitance (pF) | 0.11 | 0.16 | 0.20 | 0.24 |
|--------------------------|------|------|------|------|
| Frequency (GHz)          | 5.8  | 5.6  | 5.4  | 5.2  |
| SAR (W/Kg)               | 1.1267 | 1.1361 | 1.1445 | 1.0872 |

Abbreviation: SAR, Specific absorption rate.
| Slot geometry  | 28 Rectangular | 6 Rectangular | 29 Annular | 30 Annular | 31 Rectangular | 32 Rectangular | 21 Annular | 33 Rectangular | This work rectangular |
|----------------|----------------|---------------|------------|------------|----------------|----------------|------------|----------------|----------------------|
| Element size   | 40 × 26 mm²    | 64 × 7 mm²    | R = 12.5 mm | R = 11 mm  | 27 × 25 mm²    | 23 × 20 mm²    | R = 10.1 mm | 87 × 3.2 mm² | 18 × 2 mm²           |
| Ground size (mm²) | 62 × 52.8   | 130 × 74      | 50 × 50    | 40 × 40    | 27 × 25        | 46 × 20        | 120 × 60    | 304 × 130       | 140 × 6              |
| No. of diodes/varactors per element | 2            | 1             | 3          | 2          | 3              | 2              | 1          | 2              | 2                    |
| Covered frequency bands (GHz) | 1.5, 1.6, 1.8, 1.9, 2.24 | 698:960, 1710:2690 | 2.43, 2.85, 3.33, 4.4 | 2.5, 5.2 | 2.3, 5.8, 2.3/4.5, 4.51/5.8 | 2.5, 5.0, 5.5 | 1.8:2.5 continuous tuning | 1.82, 1.93, 2.10 | 5.1:5.9 continuous tuning |
| Max Efficiency (%) | 68, 72, 78, 76, 60 | 50:95 | 93, 96 | 55, 75, 65/66, 76/64 | 41, 83, 86 | 51, 67, 71.5, 72, 73 | - | 81, 73, 63, 52 |
| Peak R. Gain (dBi) | 1.7, 2.2, 2.5, 1.75, 1.2 | - | 2.5, 2.7, 3.6, 5.3 | 2.1, 2.8 | 0.3, 2.5, 0.7/2.3, 1.8/2.8 | 0.05, 2.9, 2.44 | −2.6, 0.5, 2.1, 2.36, 2.43 | 5.7, 5.6, 6.0 | 5.4, 5.1, 4.6, 3.9 |
| No. of elements | 1             | 2             | 1           | 1           | 1              | 2              | 4          | 1              | 4                    |
| Possible MIMO configuration | No           | Yes           | No          | No          | No             | Yes           | Yes        | No             | Yes                  |
cheek is about 10 mm. To evaluate the SAR values, input power of 13-dBm (20 mW) was applied to each port in HFSS software. The calculated 1-g SAR values for different varactor capacitance at resonance frequency are introduced in Table 3. As noted, the SAR values are well below the industry specified SAR limit of 1.6 W/kg for 1-g tissue, prescribed by FCC.

6.1 State-of-the-art comparison

To clarify the merits of the proposed design, the features of the antenna are compared in Table 4 with other related frequency-reconfigurable slot antenna designs available in the literature. As noted, the proposed antenna has many desirable features, it provides a wide continuous tuning range, a small number of diodes to achieve tuning, a compact structure, high efficiency and gain, and maximum number of elements in a small ground size. It is obvious from Table 4 that the proposed array is one of the distinguished work of slot-based antennas existing in literature.

7 CONCLUSIONS

A four-element frequency-reconfigurable slot MIMO antenna array is proposed for smartphones with metal-casing. The challenge of extremely narrow return loss bandwidth that are inherent for a slender slot antenna was overcome through frequency reconfiguration in four steps to cover the frequency range of 5.1–6 GHz. Frequency reconfiguration was achieved using varactor diodes. Starting from a design in free space the effects of implementing the antenna using FR4 substrate and real varactor diodes on the antenna were studied. It was found that FR4 does degrade the antenna efficiency and the gain and thus if possible other low loss substrates could be used. Further losses are incurred due to the varactor resistance, which can be circumvented by employing even lower loss varactors or switched capacitors. Experimental results generally validate the simulation results. Current distributions and electric fields computed delineate that the antenna elements are generally isolated from each other. MIMO performance for the antenna when compared to the reference case of a Raleigh distribution and SISO case demonstrated excellent performance.

Effects of a generic battery and LCD on frequency reconfiguration and antenna efficiency were also studied. The results revealed that the frequency reconfiguration was unaffected, and the antenna efficiency was minimally affected at the two higher frequencies. At the two lower frequencies, efficiency degraded slightly due to small deterioration in the antenna radiation efficiency. Port-to-port antenna isolation was greater than 20 dB which deteriorated to 15 dB in the presence of a battery and an LCD. Moreover, the MIMO performance and user effect on the proposed antenna were evaluated, and results confirmed that the antenna yields excellent response.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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