Multiple-input-multiple-output antenna with pattern reconfiguration and correlation reduction for WLAN applications

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Abstract
A Yagi-Uda inspired novel pattern reconfigurable multiple-input-multiple-output (MIMO) antenna array is proposed in this article. The antenna consists of two co-axially excited microstrip patch radiators with modified ground plane. A conducting strip with an integrated PIN diode is optimally placed midway between two MIMO patch radiators placed at a distance of \(0.22\lambda_0\) \((\lambda_0\) is the free space wavelength at 2.4 GHz) apart. By switching the diode OFF or ON, the conducting strip directs or reflects the main beam of the two MIMO elements at an angle of \(\pm30^\circ\) or \(\pm60^\circ\), respectively, thereby, enabling 30\(^\circ\) wideband scanning and four switchable beams radiated by the two antennas. The novel MIMO antenna exhibits 17 dB isolation improvement between the two radiators when the diode is switched ON as a result of the beam deflection. For all switching modes, the MIMO antenna demonstrates an average gain and efficiency of 5 dB and 92\%, respectively, at the resonance frequency of 2.4 GHz. The novel antenna is fabricated and measured to verify the simulation results. This simple, low-cost, efficient, and mutually isolated antenna array can be very useful in MIMO WLAN applications.

KEYWORDS
antenna, envelope correlation coefficient, mutual coupling reduction

1 | INTRODUCTION

Antenna engineers have been exploring multiple-input-multiple-output (MIMO) technology recently due to their inherent advantages such as increasing signal-to-noise-ratio, spectrum efficiency and channel capacity, especially in a multipath environment.\(^1\)\(^-\)\(^3\) Also, because of the emerging handheld nature of smart devices, patch antennas have been commonly used in MIMO antennas due to their simplicity, flexibility and low cost. However, MIMO patch antennas usually suffer from mutual coupling because of the undesired surface waves radiating inside the substrate, space waves transmitted among individual elements of the array, as well as the surface waves propagating through the ground plane.\(^4\) This coupling
increases as the distance between the antenna elements reduces, with the aim of maximizing space for other electronic components. High mutual coupling can degrade the throughput and the efficiency of the antenna array. Also, increasing wireless system capacity without increasing the available bandwidth is always limited by the correlation of the antenna elements.

Mutual coupling in MIMO antennas has been proven to be mitigated by the use of decoupling structures. Metamaterial structures and defective ground plane are used as decoupling structures in literature to increase the isolation ($S_{21}$) between two patch antennas by 10-40 dB in the frequency range of 4.0-6.5 GHz. In Reference 6, double-layer metamaterial absorber was used between four microstrip patch antennas to accomplish 8-11 dB isolation improvement, with peak realized gain of 2.3 dB at 1.26 GHz. Fractal decoupling structure was proposed to reduce the mutual coupling between the elements of a planar inverted-F antenna array by 8-32 dB, with peak gain of 2.3 dB between 3.17 and 4.15 GHz. The authors in Reference 8 placed a resistor between four parallel-coupled resonators to achieve 25 dB isolation improvement between 6 and 7 GHz. In Reference 9, meander lines and H-shaped strips were combined to achieve about 27 dB isolation improvement between 2.2 and 2.7 GHz in a high density patch antenna array, with 84.1% radiation efficiency. By investigating the E- and H-field distributions in a near field resonator placed above two patch antenna elements, a 20 dB isolation improvement was achieved, with maximum efficiency of 80% around 2.23 GHz in Reference 3. A 16.6 dB maximum mutual coupling reduction was achieved in a three-element E-plane array antennas using metal vias and defected ground surface, with maximum gain and efficiency of 4.5 dB and 78%, respectively, between 3.95 and 4.04 GHz.

Three inter-digital lines are placed among three patch antennas to achieve 24.7 dB maximum isolation improvement at 5.8 GHz. Also, the authors in Reference 12 presented a novel hybrid electromagnetic structure and defected ground surface, which were employed to achieve 22 dB isolation enhancement between two patch antennas at 4.9 GHz. In Reference 13, the authors employed slotted-EBG structure to isolate MIMO patch antenna array at 28 GHz millimeter-wave frequency. Also, in Reference 14, asymmetric loop resonator was deployed to achieve 15 dB mutual coupling reduction and maximum efficiency of 80% in a V-slot patch antenna between 2 and 5 GHz.

The efficiency of a MIMO antenna can also be increased by reducing the envelope correlation coefficient (ECC) of the elements. This is usually realized by pattern reconfiguration. In literature, PIN diodes are used as switches to implement MIMO antennas with pattern reconfiguration, reduced ECC and mutual coupling between the antenna elements. In Reference 16, fixed dipole lengths are manipulated to reconfigure radiation patterns with improved mutual isolation and antenna efficiency. Two switches are employed in a loop-and-dipole antenna to generate three beams at more 21 dB isolation level ($S_{21}$) in all modes, low ECC, 5.4 dB peak gain and 78% peak total efficiency between 5.15 and 5.25 GHz. In Reference 18, eight PIN diodes are integrated into a MIMO microstrip U-slot antenna operating at 5.32 GH to achieve dual switched beams with a mutual coupling less than -20 dB in all switched modes, with maximum gain and efficiency of 6.5 dB and 86.6%, respectively. In Reference 19, the authors utilized six PIN diodes to achieve seven scanning angles using a simple printed antenna array with efficiency of 85% and a gain of 5.5 dB maintained throughout the switching modes at 3.6 GHz. Two PIN diodes were inserted in the driven element of pair of Egyptian dipole antenna and two metallic strips to achieve two switchable beams, with maximum efficiency and gain of 80.6% and 4.78 dB, respectively, at 1.8 GHz in Reference 20. Also, in Reference 21, two varactor diodes were employed in a Yagi-Uda printed dipole antenna at 2.4 GHz to achieve two tilted beams with maximum efficiency of 70% and peak gain of 6.1 dB, respectively. The radiation pattern of a magneto-electric dipole antenna was altered to achieve two tilted patterns at ±26° using thirty PIN diodes, with peak efficiency of 85% in the 1-1.82 GHz bandwidth. The authors in Reference 23 presented a cylindrical dielectric resonator antenna (DRA) with four PIN diodes to achieve four different beam tiltss with maximum gain of 9.74 dB over 5.25-6 GHz. Also, three PIN diodes were used to achieve three end-fire pattern tilts in a compact monopole parasitic antenna, with 6.6 dB maximum gain around 2.2 GHz in Reference 24. Loop antenna with pattern scanning from +40° to -40° using six diodes with maximum gain of 2.1 dB over 0.8-1.15 GHz was presented in Reference 25. The reverse voltage of two varactors, mounted on the two slot lines which are connected to two slotted antennas, was controlled to achieve three pattern reconfiguration, with 6.5 dB maximum gain at 2.4 GHz. In Reference 27, a compact microstrip antenna capable of six different beam tilts with six PIN diodes within 3.5-3.9 GHz, and maximum efficiency and gain of 86% and 6 dB, respectively, was presented. Also, an electronically-switchable parasitic antenna array with three pattern tilts using two PIN diodes with maximum efficiency and gain of 97% and 5.92 dB, respectively, around 5.9 GHz was reported in Reference 28. In Reference 29, two beam tilts using two PIN diodes in a 3D cubic slot antenna were reported, with peak gain of 4.2 dB around 2.4 GHz. In Reference 30, a circular patch antenna with broadside and conical beam operations was presented, using 20 PIN diodes, with resonance frequency around 2.55 GHz, peak gain of 7.7 dB, and port isolation improvement.
of 13 dB. Also, in Reference 31, four PIN diodes are incorporated in the feed network of an arc dipole reconfigurable antenna to realize four switchable beams, with peak gain and efficiency of 5 dB and 60%, respectively, over 2.25-3.16 GHz. In Reference 32, four PIN diodes were employed to realize four scanning angles in a printed monopole antenna around 4.3 GHz.

It is noteworthy that most of the aforementioned designs either employ sophisticated structures\textsuperscript{4,6,13,26,29} or demonstrate low efficiency.\textsuperscript{17,21,31} Therefore, this article proposes a simple microstrip MIMO antenna array designed using the Yagi-Uda principle. The antenna comprises two driven elements and one parasitic element that are coupled through near-field and surface waves. The dimensions of the driven elements are dependent on the antenna resonant frequency, while the dimensions of the parasitic element are controlled electronically using PIN-diodes acting as a director or reflector depending on its lengths, based on the Yagi-Uda approach. Hence, the phase delay between the driven and parasitic elements introduces the desired tilt in the main radiated beam. Two square patches with modified ground planes are used as driven elements of the 2.4 GHz MIMO antenna. A conductor strip with an integrated PIN diode is used as a switched parasitic element and is optimally placed between the driven elements. Consequently, the main beams of the driven elements are steered in the desired direction based on the switching state of the diode. Compared to previous literature, this work presents simple patch MIMO antenna capable of radiating four switchable beams with just a single switch with very high efficiency of 95% and isolation improvement of 17 dB. Numerical results obtained using the CST commercial simulation tool are verified with measured s-parameters and radiation patterns. The article is organized as follows: Section 2 explains the reconfigurable MIMO antenna array design where the antenna is developed from Yagi-Uda principle to enable pattern reconfiguration with reduced coupling, Section 3 explains the simulated and measured results, and Section 4 concludes the article.

2  RECONFIGURABLE MIMO ANTENNA DESIGN

This section explains the design and operational principles of the proposed MIMO pattern reconfigurable and coupling reduction antenna array. The proposed MIMO antenna is designed using the Yagi-Uda principle\textsuperscript{33,34} for microstrip antennas, where constructive mutual coupling between the driven and parasitic elements is maintained, and destructive mutual coupling between the two driven elements is suppressed depending on the radiation patterns of the individual elements of the MIMO antenna. Figure 1 depicts the top and back view of the proposed antenna designed to resonate at WLAN frequency of 2.4 GHz. The antenna consists of two square driving elements each of length \( W_p \) and separated by \( L_r = 26.7 \) mm or 0.22\( \lambda_0 \) (\( \lambda_0 \) is the free space wavelength at 2.4 GHz). A rectangular copper strip of dimensions \( L_d \times W_p \) with an integrated PIN diode is placed equidistantly from the two driving elements at \( S = 30 \) mm from the middle of each patch. The parasitic element, located midway between the two driven elements (see Figure 1A), acts as a director when the PIN diode is switched OFF, hence, having a minimal effect on the radiation pattern of the two antennas. The parasitic element also acts as a reflector when its integrated PIN diode is switched ON, thereby, further tilts the radiated beams of the two antennas in opposite direction and help reduce the array correlation measured by the ECC. This behavior of the parasitic element as a result of the switching state of the diode is based on the Yagi-Uda Principle. This principle specifically requires that the reflector or director be located at approximately a quarter wavelength distance from the middle of the driven element,\textsuperscript{33} this distance is chosen as \( S = 30 \) mm or 0.24\( \lambda_0 \) in this article. The ON state of the diode is modeled in CST simulation tool as RLC circuit where \( R = 4.7 \) k\( \Omega \), \( L = 0.15 \) nH, and \( C = 0 \) F, all connected in series. The OFF state of the diode is modeled as \( R = 7 \) k\( \Omega \), \( L = 0 \), and \( C = 0.017 \) pF, all connected in parallel.

When the switch is ON, the copper strip is serving two functions. First, reflects the radiations of the two patches, because its length is longer than the driven patches. Second, it acts as a decoupling structure for the two MIMO patch elements because it suppresses the surface wave interactions between the two antenna elements owing to the radiation pattern tilt. This consequently leads to a decrease in the ECC of the MIMO antenna, which will be thoroughly investigated in the next section. The antenna is printed on Rogers RO3003 substrate with dielectric constant of 3, loss tangent of 0.001, and thickness 1.52 mm. Figure 1B shows the partial ground plane of the two-element MIMO antenna with dimensions \( L_g \times W_g \). The pattern reconfiguration ability of the antenna depends on the width (\( W_g \)) of the partial ground that needs to be less than the length of the reflector as explained in the next section. It is noteworthy that the width of the reflector (\( d \)) should be approximately 0.05\( \lambda_0 \) for maximum deflection of the radiated beams. Employing the commercial numerical CST tool, the thoroughly optimized dimensions of the radiating system are \( L_d = 49.2 \) mm, \( W_p = 34.8 \) mm, \( d = W_g = 6 \) mm, \( L_g = 43.8 \) mm, \( L_r = 26.5 \) mm.
3 | RESULTS AND DISCUSSION

This section explains the simulated and measured results of the proposed antenna structure. According to the Yagi-Uda principle, the proposed antenna in Figure 1 is simulated and analyzed when the integrated diode is switched OFF and ON. When the switch is OFF, the parasitic element acts as a director as its length is shorter than that of the driven elements. But during the ON state, the strip acts as a reflector because its length becomes longer than that of the two driven elements. Figure 2 depicts the top and back view of the fabricated prototype.

3.1 | S-parameters

The simulated and measured reflection coefficients for the ON and OFF states are depicted in Figure 3. It is obvious that the 1X2 MIMO antenna resonates around 2.4 GHz with a good agreement between the measured and simulated results for both ON and OFF states. Figure 4 depicts the simulated and measured isolation between the MIMO antennas in both
OFF and ON states of the PIN diode. When the diode is switched ON by applying a DC bias voltage of 0.707 V, about 17 dB isolation improvement is noticed between the two MIMO antenna elements at the design frequency of 2.4 GHz. This improvement can be attributed to the surface wave suppression between the two antenna elements and deflection of the radiated beams, which will be further explained in the next section. Also, the measured \( S_{21} \) reasonably agrees with the simulated results, especially at the resonant frequency of 2.4 GHz. The discrepancy between the simulated and measured results are attributed to the differences in the properties of the substrate material and PIN diodes used in simulation and fabrication.

It should be noted that the DC biasing lines usually used with PIN diodes are not needed here since the AC excitation from the coaxial feed is already separated from the PIN diode. Table 1 summarizes the switching states of the MIMO antenna.

### Table 1 Switching modes for the MIMO reconfigurable antenna

| Switch state | Antenna 1 beam angle | Antenna 2 beam angle |
|--------------|----------------------|----------------------|
| OFF          | -30°                 | 30°                  |
| ON           | -60°                 | 60°                  |

3.2 Radiation patterns of the MIMO antenna

The beam deflection can be proven by the H-plane (ie, Y-Z plane) radiation patterns of the two MIMO antennas as demonstrated in the 2D pattern of Figure 5 at 2.4 GHz. Note that when the diode is OFF, the main beams of the two antennas are directed at -30° (antenna 1) and 30° (antenna 2). When the diode is ON, the reflector element (ie, strip line) further deflects the radiation patterns of the two antennas in the same direction, hence, the angles of antenna 1 tilts to -60° while antenna 2 tilts to 60°. This extra 30° tilt in both antennas is responsible for the 17 dB reduction in
Figures 6 and 7 show the 2D radiation patterns of the MIMO antenna in X-Y and X-Z planes, respectively. The radiation patterns in those planes are unaffected by the switching states of the PIN diode. Hence, the patterns are shown when the diode is switched ON. For more obvious description of the antenna performance, the 3D radiation patterns of the antenna are demonstrated in Figure 8 for both ON and OFF states of the PIN diode. It can be observed that the beam of the individual elements of the MIMO antenna tilts more (30°) in the same direction when diode is switched ON.
F I G U R E 7 Radiation patterns of the proposed pattern reconfigurable MIMO antenna in the X-Z plane at 2.4 GHz: A, Antenna 1 when switch is ON, and, B, Antenna 2 when switch is ON.

F I G U R E 8 3D Radiation patterns of the proposed pattern reconfigurable MIMO antenna at 2.4 GHz: A, Antenna 1 when switch is OFF, B, Antenna 2 when switch is OFF, C, Antenna 1 when switch is ON, and, D, Antenna 2 when switch is ON.

T A B L E 2 Comparison between the 3-dB beam widths of all cases

| Switch state | Antenna 1 beam width | Antenna 2 beam width |
|--------------|----------------------|----------------------|
| OFF          | 162°                 | 162°                 |
| ON           | 148°                 | 148°                 |

Moreover, Table 2 shows a comparison between the 3-dB beam widths of the MIMO elements in all switching cases. It is clear that the beam widths of both antennas reduce slightly when the switch is ON, and this can be an indication of a slight gain increase at the ON state of the diode as will be demonstrated later in this article.

3.3 Effect of the ground plane

The tilting angles of the radiated beam are highly dependent on the dimension of the ground plane. Any change in the width $W_g$ of the ground plane disrupts the beam angle. If the substrate is fully covered with a ground plane,
the radiated beam would tilt toward 0°, irrespective of the switching mode because the ground plane will be the main reflector in this case. Figure 9 depicts the effect of changing the width dimension of the partial ground plane for the ON state of the PIN diode for antenna 2, which is supposed to be deflected at 60° as shown in Table 1. It is obvious that as the width of the ground plane decreases, the beam tilting increases towards the intended direction of 60°. This effect is also noticeable for other switching modes. It is also observed that the beam angle slightly changes when the width $W_g$ of the ground plane is less than 10 mm. Hence, 6 mm has been chosen as the width of the partial ground of the proposed antenna as this results in a narrower beam width. Moreover, it has also been observed that the length $L_g$ of the ground plane also affects the switching ability of the antenna, just like the behavior of the width $W_g$. As the length of the partial ground plane reduces, the beam angle increases. Therefore, the length of the ground plane $L_g$ has been optimized to be 43.8 mm, which is smaller than the length of the parasitic line $L_d = 49.2$ mm in order to properly scan the beam in the required direction. Although the width of the ground plane significantly affects the radiation patterns of the antenna, it, however, moderately affects the resonance frequency as depicted in Figure 10. As the ground plane width decreases, the resonance frequency decreases as well to get closer to 2.4 GHz. The poor matching at some of the ground widths is due to the change in the matching position of the coaxial feed line as the ground size changes.

### 3.4 | Surface current distribution

The surface current distribution over the MIMO antenna array for both switching modes is depicted in Figure 11 when only antenna 1 is excited and antenna 2 is terminated with a matched load. From Figure 11A, a detectable amount of the surface currents emanating from antenna 1 is moderately coupled to antenna 2 when the diode is OFF. This is due to the 0.22λ₀ distance between the two antennas. However, when the diode is ON, the reflector further tilts the beam of
antenna 1 and thus preventing most of the surface current from getting to antenna 2 without increasing the edge-to-edge distance between the antennas, thereby, increasing the isolation as shown in Figure 11B. The beam tilting is obvious because of the low surface current shown in antenna 2 as antenna 1 is excited. If antenna 2 is excited, the same scenario will occur, with more surface current evident in antenna 2 and less surface current in antenna 1. Figures 12 and 13 show the surface current distribution as arrow plots in both switching cases (OFF/ON) for port 1 and port 2. It can be seen that the arrows are more noticeable in both antennas when the diode is switched OFF. However, when the diode is switched ON, the parasitic element between the antennas serves as reflector that now reflects most of the surface currents, hence an increase in isolation, and almost no surface currents in the second antenna.

Figures 14 and 15 show the ground plane surface currents of the proposed antenna when antenna 1 is excited and antenna 2 is terminated with a matched load, for both OFF and ON cases, respectively. It can be observed from these
figures that some of the ground surface currents emanating from antenna 1 is moderately coupled to antenna 2 when the diode is OFF. However, when the diode is ON, the reflector further tilts the beam of antenna 1 and thus preventing the surface current from getting to antenna 2, while the ground surface current in antenna 1 is more obvious due to the tilting.

3.5 Envelope correlation coefficient

To further verify the isolation-improvement capability of the proposed MIMO antenna, the ECC, which is an important performance criterion in MIMO antenna, is studied. The ECC can be calculated based on the S-parameters or the far-field characteristics of the antenna. ECC based on far-field parameter considers the radiated beam direction, while ECC based on S-parameters considers the port characteristics of the two antennas. ECC based on far-field properties is considered more indicative of the isolation capability, although it is costly because of the need to measure the radiation patterns of the antenna. ECC value less than 0.5 is generally considered acceptable for MIMO antennas. The ECC based on S-parameters is calculated using:\(^{(35)}\)

\[
ECC = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{|1 - |S_{11}| - |S_{21}|)(1 - |S_{12}| - |S_{22}|)|. \tag{1}
\]

The ECC based on far-field is calculated using:\(^{(35)}\)

\[
ECC = \frac{\left| \int_{4\pi} A_1(\theta, \phi) \ast A_2(\theta, \phi) d\Omega \right|^2}{\int_{4\pi} |A_1(\theta, \phi)|^2 d\Omega \int_{4\pi} |A_2(\theta, \phi)|^2 d\Omega}, \tag{2}
\]

where \(A_1(\theta, \phi)\) is the field pattern when antenna 1 is fed and antenna 2 is terminated by 50 \(\Omega\) load.

From Figure 15, it is clear that the ECC based on far-field is around \(-22\) dB at the resonant frequency of 2.4 GHz when the switch is OFF and around \(-27\) dB when the switch is ON, thus, having an improvement of about 5 dB.
the ECC based on S-parameters is demonstrated in Figure 17. It can be observed from Figure 17 that the ECC based on S-parameter is about $-22$ dB when the diode is switched OFF and about $-41$ dB when the diode is switched ON at the resonant frequency of 2.4 GHz, thus, having an improvement of 19 dB. These results highly indicate that the mutual coupling between the two antennas can be effectively mitigated by switching the diode ON.

4 | MIMO ANTENNA EFFICIENCY AND GAIN

The simulated radiation efficiency and gain of the proposed antenna are depicted in Figures 18 and 19, respectively. It is evident from Figure 18 that the antenna exhibits radiation efficiency of about 91% when the diode is switched OFF and...
about 93% when the diode is switched ON at the resonant frequency of 2.4 GHz. This slight increase in efficiency is a result of the reduction in mutual coupling between the two antennas. From Figure 19, the antenna exhibits a gain of about 4.5 dB when the diode is switched OFF and 5.3 dB when the diode is switched ON, thus, having a slight improvement. The increase in the antenna gain is also a result of the mutual coupling reduction between the two driven radiating elements. The reduced mutual coupling is a result of the further deflection of the radiated beams of the MIMO elements when the diode is switched ON.

### 4.1 Four elements MIMO antenna design

To confirm the MIMO operation of the proposed antenna system, a four-elements MIMO configuration is simulated and the results are presented. Figure 20 shows the 1x4 MIMO configuration of the proposed antenna. Figure 21 shows the simulated reflection coefficients of the 1X4 proposed pattern reconfigurable antenna. It is obvious that there is a little resonance shift in antennas 2 and 3 (ie, \(S_{22}\) and \(S_{33}\)) mostly due to the existence of two parasitic elements surrounding each of these antennas. Also, Figure 22 shows the transmission coefficients of the antennas when the three diodes placed at the centre of the parasitic elements are switched on. It can be seen that the antennas exhibit good isolation properties.
at 2.4 GHz. Moreover, it is noticed that both \( S_{21} \) and \( S_{43} \) are the same while \( S_{32} \) is different. This behavior can be attributed to the fact that both antennas 2 and 3 are surrounded by two parasitic elements each, whereas this is not the case for antennas 1 and 4. Consequently, more coupling introduced between antennas 2 and 3.

Table 3 compares the characteristics of our proposed antenna to the current state-of-the-art. It is clear that our proposed antenna offers the highest radiation efficiency and isolation enhancement, with moderate gain, using just a single diode to achieve 4 scanned beams. It is also obvious from the table that our design exhibits the highest ratio between the number of scanned beams to the number of electronic switches employed.

### 5 | CONCLUSION

This article presents a simple and efficient pattern reconfigurable microstrip MIMO antenna array that consists of two square driven elements placed on both sides of a rectangular parasitic element. By optimizing the ground plane size and the location of the shared parasitic element, the designed antenna demonstrated four scanning beams with just a single diode switch. The effect of the width of the ground plane on the radiation characteristics of the antenna as well as the resonance frequency of the antenna have been analyzed. By turning the switch on, a 30° beam tilting increase is observed in the radiation patterns of both antenna elements, as well as 17 dB isolation improvement between the two driven elements. For both switching modes of the proposed MIMO antenna, the ECC values based on far-fields and S-parameters are better than \(-20\) dB. Also, there was a slight increase in the antenna gain and efficiency as a result of the isolation improvement. Additionally, 1x4 MIMO configuration of the proposed antenna is presented to validate the proposed technique. The measured results agreed well with the simulated data. This simple efficient antenna is an excellent candidate for MIMO WLAN applications.

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### CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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