Fluidically Reconfigurable MIMO Antenna With Pattern Diversity for Sub-6-GHz 5G Relay Node Applications

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Abstract—A four-element frequency reconfigurable and pattern diverse multiple-input–multiple-output (MIMO) antenna array for fifth-generation relay node applications is presented to operate in LTE bands 42 (3400–3600 MHz), 43 (3600–3800 MHz), and 46 (5150–5925 MHz). A planar microstrip line-fed monopole antenna is utilized as the MIMO element. The antenna relies on fluidic reconfiguration mechanism to either serve LTE bands 42/43 or 46. It incorporates a substrate milled channel beneath each monopole arm to hold distilled water. The water in the channel perturbs the E-field distribution in the vicinity of the antenna arm and modifies the effective permittivity of the dielectric medium. To realize pattern diversity, adjacent elements are placed orthogonal to each other. Measured prototype exhibits a total active reflection coefficient $|\mathcal{T}\mathcal{R}\mathcal{C}|$ and $|S_{11}| \leq -10 \text{ dB}$ for the high band when the channel is vacant (case 1) and the low band when filled with water (case 2), while minimum isolation is above 19.6 dB. The peak measured gain is $\sim 4.6$ and $\sim 2.8 \text{ dBi}$, while the worst case envelope correlation coefficient (ECC) is $\sim 0.004$ and $\sim 0.016$ for cases 1 and 2, respectively. It measures $82.4 \times 82.4 \text{ mm}^2$ and was fabricated on a 1.52-mm-thick substrate of $\varepsilon_r = 3.55$.

Résumé—Un réseau d’antennes entrées multiples et sorties multiples (EMSM) à fréquence reconfigurable à quatre éléments et de diversité à motifs pour les applications de noeud de relais de cinquième génération est présenté pour fonctionner dans les bandes ELT 42 (3400–3600 MHz), 43 (3600–3800 MHz) et 46 (5150–5925 MHz). Une antenne unipolaire alimentée par ligne microruban plane est utilisée comme élément EMSM. L’antenne repose sur un mécanisme de reconfiguration fluidique pour desservir les bandes ELT 42/43 ou 46. Elle comprend un substrat de canal moulu sous chaque bras monopolaire pour contenir de l’eau distillée. L’eau dans le canal perturbe la distribution du champ E au voisinage du bras d’antenne et modifie la permittivité effective du milieu diélectrique. Pour réaliser la diversité de motifs, les éléments adjacents sont placés orthogonalement les uns aux autres. Le prototype mesuré présente un coefficient de réflexion actif total $|\mathcal{T}\mathcal{R}\mathcal{C}|$ et $|S_{11}| \leq -10 \text{ dB}$ pour la bande haute lorsque le canal est vacant (cas 1) et la bande basse lorsque remplie d’eau (cas 2), alors que l’isolation minimale est supérieure à 19,6 dB. Le gain maximal mesuré est d’environ 4,6 et de 2,8 dBi, tandis que le coefficient de corrélation d’enveloppe (ECC) dans le pire des cas est respectivement de 0,004 et 0,016 pour les cas 1 et 2. Il mesure $82.4 \times 82.4 \text{ mm}^2$ et a été fabriqué sur un substrat de 1,52 mm d’épaisseur de $\varepsilon_r = 3.55$.

Index Terms—Antennas, dielectric fluid, distilled water, envelope correlation coefficient (ECC), fifth generation (5G), fluidic, high power, microfluidics, monopole, multiple-input multiple-output (MIMO), pattern diversity, reconfigurable.

I. INTRODUCTION

The fifth-generation (5G) wireless network architecture is a heterogenous multtier system encompassing a coverage tier and a hotspot tier [1], [2]. The coverage tier provides high capacity, reliable, and wide coverage links, while the hotspot tier is dedicated to high data-rate, short-range, and primarily indoor links [2]. For the 5G Coverage tier, the 3400–3800-MHz frequency band comprising of long-term evolution (LTE) bands 42 and 43 has been allocated [3]. Moreover, to allocate more bandwidth, the LTE license assisted access (LTE–LAA) band (5150–5925 MHz) is also provided in the sub-6-GHz regime. 5G will utilize the multiple-input–multiple-output (MIMO) antenna technology to obtain the best data rate for a given frequency bandwidth and allowable power levels [4]. MIMO antennas perform the best when they fully utilize a rich scattering environment. However, if MIMO antennas with pattern diversity are employed, they show good performance even in poor scattering environments [5].

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Many studies reveal that in the coverage tier, MIMO antennas in the relay nodes are anticipated to play an important role in 5G to provide extended coverage at cell edges as well as for indoor applications [6]–[9]. These nodes can provide enhanced throughput by employing nonorthogonal multiple access (NOMA) with increased relay power capacity [10]. Furthermore, such nodes need to be low profile and wall mountable. Thus, to obtain the best performance from the 5G relay nodes in LTE 42, 43, and 46 bands, planar, pattern diverse, and frequency reconfigurable MIMO antennas with high-power handling are highly suitable.

Recently, in the field of reconfigurable antenna, the fluidic mechanism for reconfiguration due to their liquid nature has attracted a lot of attention to overcome limited reliability of mechanically triggered counterparts. Easy movement of fluid eradicate issues arising from the movement of solid parts that cause fatigue, wear, and tear [11]. Notably, the linear nature of switching element in fluidic reconfigurations enables antennas to maintain linearity in applications involving high average power. However, switching speeds are slower compared with semiconductor devices. The choices for the fluids are vast and depend on the type of application. In RF design, liquid metals have extensively been sought in design of various antennas with reconfigurable radiation pattern [11], polarization [12]–[14], and filters [15], [16]. Liquid metal-based designs face issues in integration with the antenna structure, and the residues of oxidized liquid metal in the fluidic channel are difficult to handle. Thus, even after using micropumps for automated pressurized actuations, liquid metal-based techniques remain arduous to design. To circumvent these problems, various techniques have been proposed [17], [18].

Liquid dielectric-based methods are not severely affected and present a viable alternative. Moreover, the conductivity of the liquid dielectric is usually very low, and hence, new methods for reconfiguration need to be investigated. Different types of fluids have been adopted in high-frequency design, such as ethyl alcohol [19], [20], acetone [21], transformer oil [22], and water [19], [21], [23]–[29]. In [21], a microstrip patch antenna with two microchannels integrated under the radiating edges is reported. A wide frequency tuning range is achieved with injection of dielectric liquids, such as water, acetone, methanol, and ethanol. However, the radiation efficiency is only 27%. In [23], a water-filled dielectric resonator antenna, fed with a probe, is realized on a glass container having multiple layers. For frequency tuning, the height of the antenna is varied through successive loading of the layers with water. This nonplanar design is shown to exhibit frequency tuning of 52% with respect to the center frequency. Water has also been employed to provide radiation pattern reconfiguration [27], [28] and polarization reconfiguration, as in [30]. In the antenna array regime, few fluids-based antennas have been reported. For instance, two-element water-based MIMO antenna in [24] offers good bandwidth and efficiency but with degraded ECC performance. Reference [25] implements a $2 \times 2$ antenna array using aperture-coupled water dielectric patch antenna exhibiting good gain but lacks reconfigurability. Qian and Chu [31] present the two-element water loaded pattern reconfigurable MIMO antenna with good ECC and gain but only with 11% impedance bandwidth (IBW).

In this article, a four-element frequency reconfigurable and pattern diverse MIMO array is presented. A reconfigurable low-profile microstrip line-fed monopole is utilized as the MIMO element. We first discuss the design for reconfigurable single element operating in LTE bands 42 and 43 or 46 and follow-up with a four-element MIMO array. The element orientation in the antenna aids to provide pattern diversity and, hence, lower ECC to ensure good MIMO performance with reasonable antenna efficiency over all the frequency bands of interest.

II. RECONFIGURABLE MIMO ELEMENT DESIGN

The monopole in [32] is redesigned on a 1.52-mm-thick Rogers 4003 substrate ($\epsilon_r = 3.38$, $\tan \delta = 0.0027$), as shown in Fig. 1(a), to yield 40% $-10$-dB IBW with the fixed center frequency of around 5 GHz. The ground plane size is tuned in ANSYS HFSS electromagnetic (EM) simulations to obtain a large IBW of 1.9 GHz, while the monopole width is tuned for best impedance match of $\sim 26$ dB. This reference antenna, however, can only serve the LTE band 46 with the single-band operation. Therefore, to enable antenna operation on LTE band 42/43 as well as LTE band 46, a fluidic reconfiguration mechanism is incorporated by partially milling out the substrate beneath the monopole arm open end, as shown in Fig. 1(b), to create a channel, as described in [32] and [33]. The four element MIMO antenna using this element is shown in Fig. 2. To switch operation to lower bands, the created channel is filled with distilled water. The high relative permittivity of distilled water introduces discontinuities in the modified medium. Water-filled channels perturb the $E$-field distribution around the monopole arm altering the input impedance of the
Fig. 2. Proposed four-element MIMO RMA array is shown where each antenna channel is filled with water: $L_a = 82.4$, $W_a = 82.4$, and $W_d = 10$ (rest of the design parameters are same as the RMA element shown in Fig. 1).

antenna. In effect, the effective dielectric permittivity seen by the excited waves inside the structure increases. Thus, for the monopole antenna, the $\lambda_g/4$ (where $\lambda_g$ is guided wavelength in microstrip environment [34]) resonance shifts to a lower frequency, as shown in Fig. 3. The dielectric constant and loss tangent for distilled water are modeled in EM simulations using the experimentally verified data at $20^\circ C$ ($\varepsilon_r \sim 76.9$ and $\tan \delta \sim 0.2$ at $3.6$ GHz) from [35].

As intuitively evident, for the water-filled case, more volume of water in proximity to monopole arm results in larger frequency shift; however, the bandwidth tends to reduce, as reported in [32] and [33]. To accommodate this effect, the antenna is designed with large IBW for vacant channel case. Subsequently, the depth of the water channel is varied to select the depth that offers the required bandwidth of at least 400 MHz around 3.6 GHz. Fig. 3 depicts the variation of $|S_{11}|$ as the channel depth changes from 1 to 1.48 mm for the antenna shown in Fig. 1(b). As seen, for the air-filled channel case (C1), the resonant frequency changes slightly by $\sim 3.5\%$, while for water-filled case (C2), resonant frequency shows a larger change of $\sim 13.5\%$. Furthermore, the channel depth of $1.24$ mm is selected, as it provides the required IBW and impedance match to cover LTE bands 42 and 43 (3400–3800 MHz) when filled with water (case C2) and LTE band 46 (5.15–5.925 GHz) when vacant (case C1).

III. RECONFIGURABLE MIMO ANTENNA ARRAY

A. Reflection and Isolation Characteristics

Fig. 2 shows the model of the proposed MIMO antenna with all the design parameters. In this MIMO array, four elements are used, and they are arranged such that adjacent monopole elements are orthogonal to each other. It also implies that the diagonally opposite elements are placed in opposite directions, as in [36]. Consequently, the mutual coupling between the elements is reduced, and exciting different ports results in radiation pattern diversity as the relative position of the other elements changes when different elements are excited. Furthermore, four ports are provided to excite the respective antenna element. The interelement spacing in this scenario is crucial as it impacts both IBW and the isolation between the MIMO elements. The isolation between the antenna elements is critical to obtain good MIMO performance. The higher isolation results in decoupled antenna elements leading to improved envelope correlation coefficient (ECC). Fig. 4 shows $|S_{11}|$ and $|S_{31}|$ curves to understand the IBW and isolation performance. The $|S_{21}|$ and $|S_{41}|$ curves have lower values, so they have been omitted from Fig. 4 for sake of clarity.

As the spacing $W_d$ is increased from 4 to 10 mm, the IBW improves from 1.48 to 1.9 GHz, while the minimum isolation changes from 18.4 to 22.5 since the EM coupling decreases as the spacing between the elements increases. It is evident that $W_d = 10$ mm keeps the size acceptable for relay node-based applications and maintains the required IBW and isolation better than 20 dB for all the ports. The reflection and isolation for the antenna is reported in Figs. 5 and 6 for vacant and water filled channels, respectively. It should be noted that since the antenna is symmetric with respect to
each port, the S-parameters’ results are the same irrespective of which port is excited keeping other ports terminated. Therefore, S-parameters for the case where port 1 is excited and other ports are terminated with 50 Ω are provided in this article, while other cases are assumed to be identical. In addition, the magnitude of the surface current distribution depicted in Fig. 7 clearly shows the low mutual coupling between the antenna elements. This is evident from the fact that very low surface currents are excited on other elements when port 1 is excited. Relatively, the higher coupling between elements 1 and 4 is observed when the channel is filled with water, as shown in Fig. 7(b). As a result, lower isolation is achieved in this case ($|S_{41}|$ degrades by $\sim 2$ dB). The prototype of the antenna is fabricated, as shown in Fig. 8, using the in-house LPKF circuit plotter to corroborate the simulated results. In Fig. 5, showing results for the vacant channel, the simulated and measured responses show reasonable agreement. The measured IBW is $\sim 1.9$ GHz, while the worst case isolation in the LTE band 46 is $\sim -21$ dB. In the next step, the channel is filled with distilled water from the inlet port using a syringe. The $|S_{11}|$ response shifts downward, as shown in Fig. 6 with impedance match of $-25$ dB and spanning measured IBW of 0.8 GHz, which is sufficient to cover both LTE bands 42 and 43. The RF connector model is incorporated in the simulation results to minimize the differences in impedance matching and bandwidth for the measured results compared to simulations. However, observed differences can be attributed to fabrication tolerances, mismatches caused by the glue, and possible discrepancies in modeling distilled water dielectric constant and loss tangent.

B. Far-Field and MIMO Response

The far-field response of the antenna is analyzed by exciting one port at a time and terminating rest of the ports with 50 Ω. The far-field response for the air-filled channel is first discussed. To emphasize the radiation pattern diversity of the proposed antenna, the 3-D gain pattern is presented
in Fig. 9. When port 1 is excited, the gain pattern resembles that of a $z$-directed monopole but modified due to presence of other elements in the vicinity. In this case, element 4 acts as a reflector for fields radiated in the $+y$-direction and, thus, consolidates radiation toward opposite ($-y$) direction. However, element 2 shows minimal impact on the pattern as it is placed along the null direction and similar reasoning follows for element 3 as it is located farther away.

Consequently, element 1 excitation exhibits a monopole-like pattern with dominant radiation along the $+x$, $-x$, and $-y$-directions with nulls along the $z$-axis. To further corroborate this line of reasoning, it can be observed in Fig. 7(a) that currents in element 4 have higher magnitude compared to elements 2 and 3. Hence, element 4 shows the dominant impact on radiation pattern when port 1 is excited. The simulated maximum gain observed is 4.3 dBi at 5.5 GHz. Notably, the 3-D pattern for element 3 excitation is a mirror image of the element 1 case. This is quite obvious as in this case, fields are reflected in the $+y$-direction dominantly by element 2. However, port 2 excitation shows even more diverse radiation pattern enabling radiation along the $z$-axis. Again, the pattern is monopole-like with major radiation...
in the $+x$, $-x$, and $+z$-directions due to similar reasons cited for port 1 case. However, this time element 1 acts as an effective reflector. The maximum simulated gain is again 4.3 dBi. For reasons mentioned earlier, element 4 excitation exhibits mirrored pattern with main radiation in the $+x$, $-x$, and $-z$-directions. For the second case, similar pattern diversity is observed when different ports are excited. However, due to the effect of the discontinuity created by the water in the channel, patterns are different compared with the first case. When port 1 is excited, the 3-D radiation pattern is monopole-like with the $+x$, $-x$, and $-z$ dominant directions of radiation. While port 3 pattern remains mirrored compared to port 1 results, port 2 excitation results in a similar pattern and main directions as $+x$, $-x$ and $+y$, while port 4 results being a mirror image of port 2 case, as shown in Fig. 9. Since the frequency of operation is lowered, the relative size of the elements becomes smaller as compared to the guided wavelength, and consequently, the gain reduces. Compared to the air-filled channels, where the adjacent reflecting element has a dominant effect, here, water in the channel exhibits dominance in redirecting the radiation along the null directions of the monopoles, as reported in [32].

The radiation pattern and gain for the prototype antenna are measured in the anechoic chamber to evaluate the practical performance. The measurements are carried out for principal cut planes. Since all the elements are same, measurements are presented for the case when element 1 is excited and rest of ports are terminated. Similar performance is expected for other ports. In Fig. 10, acceptable agreement between the simulated and measured patterns is observed for both the cases when channels are filled with air and water, respectively. Furthermore, the maximum measured realized gain for case 1 is around 4.6 dBi, as shown in Fig. 11, while for case 2, it is 2.8 dBi, as shown in Fig. 12. The total active reflection coefficient (TARC) is essential to evaluate the effect of mutual coupling and random signal combinations among elements in MIMO antennas and is defined as [4]

$$\text{TARC (dB)} = 10 \log \frac{\sum_{i=1}^{4} |b_i|^2}{\sum_{i=1}^{4} |a_i|^2}$$  \hspace{1cm} (1)$$

where $a_i$ and $b_i$ are incident and reflected signals at the $i$th port. For both low- and high-band operations, TARC $<-10$ dB is achieved for both simulated and measured results. Furthermore, the simulated ECC is calculated from simulated far fields in HFSS. As shown in Figs. 11 and 12, the ECC ($\rho_e$) remains considerably low to get good MIMO performance over the bands of interest. To ascertain the high-power handling capability, the behavior of antenna at higher surface temperatures due to heating may be evaluated. It is known that the temperature on microstrip antennas can reach up to 60 °C for high input power (15 W) [37]. Using the dielectric properties of water at different temperatures from [35], Fig. 13 shows the stable performance of the simulated IBW, input match, worst case isolation, and gain performance, as the temperature of the antenna increases up to 60 °C. Finally, the minimum simulated total efficiency for case 1 is 90%, while for case 2, it is 76%. Table 1 shows a performance comparison between the proposed antenna and other fluidic-based arrays.
in the high band 46. Furthermore, in the proposed MIMO simultaneous simulations were carried out to meet the require-
to switch to lower bands, the channel is filled with water, and
and LTE bands 42 and 43 for the fluidically switched case.
extract the best input reflection characteristics, gain, and
backside of the substrate. The parameters for the antenna
mechanism has been employed through easy integration of the
liquid dielectric loading-based reconfigurable
element. The liquid dielectric loading-based reconfigurable
has been reported. A simple planar and low-profile microstrip
simulated at elevated temperatures of 40
and 46. A prototype of the proposed design was fabricated and
other; thus, the antenna exhibits radiation pattern diversity and
frequency reconfigurability to operate in LTE bands 42, 43,
To switch to lower bands, the channel is filled with water, and
and simultaneous simulations were carried out to meet the requirements in these low bands while maintaining performance in the high band 46. Furthermore, in the proposed MIMO antenna, adjacent elements are placed orthogonal to each other; thus, the antenna exhibits radiation pattern diversity and frequency reconfigurability to operate in LTE bands 42, 43, and 46. A prototype of the proposed design was fabricated and measured showing good agreement with the simulated results. Furthermore, to evaluate the high input power operation and, hence, higher operating temperatures, the antenna has been simulated at elevated temperatures of 40 °C, 50 °C, and 60 °C, showing stable performance.

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REFERENCES


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