Dual-band MIMO coplanar waveguide-fed-slot antenna for 5G communications

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ABSTRACT

This paper presents two new designs of MIMO dual band coplanar waveguide (CPW)-fed-slot antennas operating in the 5G frequency band (28 and 38 GHz). The first antenna is an XX MIMO antenna and the second antenna is an XY MIMO antenna. Simulated results for the S-parameters are presented for the two antennas using HFSS. Measured results are also presented for the return loss and gain with both results showing good agreement. The current distribution, group delay, envelope correlation coefficients (ECC), and diversity gain, are also presented for both antennas. The two antennas are fabricated on a substrate having dielectric constant $\varepsilon_r = 10.7$ and substrate thickness 0.635 mm. The size of the antenna is 4.4 mm x 4.1 mm x 0.635 mm.

1. Introduction

The year 2020 is widely considered to be the year of commercial launching of 5G worldwide. The spectra of 5G can be split into sub 6 GHz and mm wave bands such as 28, 38, 60 and 70 GHz. The mm wave bands are more desirable for bandwidth availability since the sub 6 GHz band is mostly occupied [1]. For 5G communication, Ka band (at 28/38 GHz) can be allocated for frequency division duplexing (FDD), where a dual-band single antenna system is preferred as a transceiver [2, 3, 4, 5, 6].

As a key component of the LTE wireless system, the multiple-input–multiple-output (MIMO) antenna, which utilizes multiple transmitting and receiving antennas, has attracted significant attention in the past few years for its ability to increase transmission capacity and reduce multipath fading [7, 8, 9]. MIMO antennas also provide spatial diversity, polarization diversity and/or pattern diversity [4]. Integrating MIMO technology with multiband antennas can further increase the channel capacity as compared to conventional MIMO systems for narrowband applications [8].

Dual frequency antennas are used in a variety of applications including satellite communications, global positioning systems, synthetic aperture radar and personal communications systems [10, 11, 12].

The use of coplanar waveguide in multi band antennas as antenna feed is important so that the antenna will be compatible with monolithic microwave integrated circuits. Coplanar waveguide has several advantages such as easy integration with active and passive elements, low frequency dispersion, the extra design freedom through the ability to vary the characteristic impedance and phase constant by changing the slot and strip widths, and avoiding the excessively thin, and therefore fragile, substrates as in microstrip line [13, 14, 15, 16, 17, 18, 19, 20].

The design of CPW dual band MIMO antennas operating in the mm wave band for 5G has recently attracted much attention. Wei Hu et al [21], designed a dual-band eight-element MIMO array using multi-slot decoupling technique for 5G terminals with multiple PCB boards. Parchin et al [22], proposed a new broadband MIMO antenna system for sub 6 GHz 5G cellular communications that employs 4 pairs of compact CPW. Barani, et al [23], proposed low-profile wideband conjoined...
open-slot antennas fed by grounded coplanar Waveguides for $4 \times 4$ 5G MIMO operation. Abed and Jawad [24] proposed a compact size MIMO fractal slot antenna for 3G, LTE (4G), WLAN, WiMAX, ISM and 5G communications using CPW feed.

This paper proposes a MIMO coplanar waveguide (CPW) fed double folded slot dual band antenna operating at 5G (28 and 38 GHz) bands. This antenna can be used for future 5G cellular communication systems achieving high speed data rate that is possible through millimeter-wave communications with wide bandwidth system. The basic folded slot antenna cell operating in the frequency range 5 GHz and 7 GHz was
Figure 3. Comparison between measured and simulated $S_{11}$ for the single antenna.

Figure 4. Comparison between measured and simulated $S_{11}$ and $S_{22}$ parameters versus frequency for (a) MIMO XX Antenna. (b) MIMO XY Antenna.
designed using the technique in [20] which relies on generating dual band antenna by using a double folded slot antenna which is used to reduce the impedance for matching, as shown in Figure 1 (a). In this technique, we made use of the study by [12] and [13], which indicated that the impedance of CPW folded slot antenna can be lowered so that it approaches that of the feed line for matching by increasing the width of the slot arm that is farther from the feed. No other dimension had to be changed.

The proposed MIMO (XX) and MIMO (XY) antennas are generated by mirroring the basic antenna cell in two orthogonal directions, as shown in Figure 1 (b) and (c). The same method was used in [9] to generate the Pacman-shaped UWB MIMO antenna. In the following, we design the MIMO antennas to operate at 28 GHz and 38 GHz. Then the return loss and gain pattern are obtained using simulation and measurement. We also find the envelope correlation coefficient (ECC) [9, 25, 26, 27] which determines how much the communication channels are isolated. In other words, it describes how much the radiation patterns of two adjacent antennas affect each other. We also find the group delay and directive gain.

The advantage of the proposed antenna is that it operates in the 5G high frequency range (28–38 GHz) with what this entails in terms of future applications in the wireless communications industry. It is an easy to design dual band MIMO antenna which employs CPW as the feed with the advantages of CPW in terms of its compatibility with monolithic microwave integrated circuits (MMIC). The size of the antenna is also small compared to other antennas. The antenna showed very good performance in terms of ECC, Diversity Gain DG, group delay, return loss and radiation pattern.

2. Antenna measurement and analysis

The basic antenna to be considered is a dual band antenna that operates at 28 and 38 GHz. It consists of a CPW line of 50 Ω impedance having a strip width of 0.255 mm and a slot width of 0.129 mm feeding a double folded slot antenna, as shown in Figure 1 (a). The RT/Duroid 6010LM substrate from Rogers is used for the design, the substrate has ε_r = 10.7 and substrate thickness of 0.635 mm. The double folded slot is

![Comparison between measured and simulated S12 parameter versus frequency for (a) MIMO XX Antenna. (b) MIMO XY Antenna.](image-url)
used to reduce the impedance of the slot antenna for matching purposes, more details can be found in [20].

The proposed antenna is simple to design. It consists of a feed CPW line that has an impedance of 50 Ω (strip = 0.255 mm, slot = 0.129 mm). This can be obtained using quasi static formulas available in the software IE3D of Zeland Inc. [28]. The feed CPW is connected to two folded slot antennas as shown in Figure 1a. The total (outer) slot antenna loop resonates when its length is about $\lambda_g (=4.514 \text{ mm})$ where $\lambda_g$ is the guided wavelength of CPW at the lower operating frequency of 28 GHz. The smaller (inner) slot antenna resonates when its length is about $\lambda_g (=3.326 \text{ mm})$ where $\lambda_g$ is the guided wavelength of a CPW at the higher operating frequency of 38 GHz. This yields approximately $h_1 = 1.924 \text{ mm}$ and $h_2 = 1.387 \text{ mm}$ (see Figure 1a) which are chosen as the starting values to be entered in HFSS. These values ignore the coupling between the loops and the effect of changing the width of the outer slot. Therefore $h_1$ and $h_2$ are then modified using HFSS to yield the correct values for $f_L = 28 \text{ GHz}$ and $f_H = 38 \text{ GHz}$. The resultant $h_1$ and $h_2$ are given in the Figure 1a ($h_1 = 1.796 \text{ mm}, h_2 = 1.360 \text{ mm}$). For matching the antenna to the feed CPW line, the width of the outer slot is increased from 0.123 mm to 0.363 mm.

The basic antenna of Figure 1 (a) is flipped horizontally and vertically to generate two different antenna types, a MIMO XX and MIMO XY antenna as shown in Figure 1 (b) and (c), respectively. Simulations of the antennas of Figure 1 were carried out using HFSS.

As for measurement, our Network Analyzer operates up to 20 GHz. For this reason we had to scale the dimensions of Figure 1, including the substrate thickness, by multiplying by a factor of 3. This is shown in Figure 2 (a, b, c). The measured substrate is 1.905 mm thick with $\varepsilon_r = 10.7$.

The return loss of the single antenna for measured and simulated results are given in Figure 3, the measured and simulated results compare very well.

The scattering parameters measurements for the two MIMO antennas are shown in Figures 4 and 5. Figure 4 shows the return loss of the measured and simulated results for the two MIMO designs, and
Figure 5 illustrates the $S_{12}$ parameter results for the XX and XY MIMO designs. It is evident that measurement and simulation results are in good agreement.

The current distribution of the MIMO antenna is calculated using HFSS as shown in Figure 6 and 7 for the MIMO XX and MIMO XY configurations, respectively. It is clear that the larger slot loop is responsible for radiation at the lower frequency of 28 GHz and the inner slot loop is responsible for radiation at the upper frequency of 38 GHz.

The group delay was obtained using HFSS. It is shown in Figure 8 (a,b) for the MIMO XX and MIMO XY, respectively. The group delay is small and increases at the two operating frequencies of 28 GHz and 38 GHz.

The antenna radiation patterns were measured using Desktop Antenna Measurement System (DAMS), DAMS is a versatile multiple axis antenna measurement system used for antenna radiation pattern measurements. This system features 360 degrees of azimuth with up to +/-90 degrees of tilt. Rotary tables with stepper motors, linear actuators and vector network analyzers are incorporated in this system to facilitate the measurement process of the radiation characteristics of the antenna under test. Software used for automated antenna measurement is Antenna Measurement Studio by Diamond Engineering. This provides precision antenna measurements with data processing capability. The measurement setup used includes a stationary calibrated horn antenna (Reference/Transmitter Antenna), the DAMS system and Vector network analyzer. The simulated and measured gain pattern versus frequency were plotted in the elevation (y-z) plane as shown in Figure 9 (a, b, c) for the single and the two MIMO antennas. Good agreement is obtained.

The envelope correlation coefficient ECC can be obtained from the 3D radiation pattern, but this involves numerical integrations and 3D radiation pattern measurements [25]. For a single mode lossless 2 MIMO antenna, a simplified expression for the ECC using the scattering parameters, can be expressed as follows [26, 27]: The envelope correlation coefficient ECC was calculated using the formula

$$
ECC = \frac{\tilde{S}_{11}S_{12} + \tilde{S}_{21}S_{22}}{\sqrt{[1 - |S_{11}|^2][1 - |S_{22}|^2]}}
$$

(1)

where $\tilde{S}_{11}$, $\tilde{S}_{12}$ are the complex conjugates of $S_{11}$ and $S_{12}$, respectively. A value of 0.5 for ECC or less is adequate for low correlation between the antenna elements [25]. Figure 10 (a,b) shows the ECC versus...
frequency for the MIMO XX and MIMO XY antennas, respectively. Both figures indicate low correlation between the antenna elements.

Diversity gain (DG) is defined as the difference between the combined signal from all the antennas of the diversity system and the signal from a single antenna, which can evaluate the diversity performance of MIMO antenna [29]. In a simple word, if DG is higher, the improvement in diversity performance is better. The DG is obtained using the formula [29]:

\[
\rho_e = \frac{\iint_{\Omega} F_1(\theta, \varphi) \times F_2(\theta, \varphi) \, d\Omega}{\iint_{\Omega} |F_1(\theta, \varphi)|^2 \, d\Omega \, \iint_{\Omega} |F_2(\theta, \varphi)|^2 \, d\Omega}
\]  

(2)

\[
DG = 10 \sqrt{1 - \rho_e}
\]  

(3)

Where \(\rho_e\) is the cross correlation between the far fields of the MIMO when antenna element 1 and 2 are excited resulting in far fields \(F_1(\theta, \varphi)\) and \(F_2(\theta, \varphi)\), respectively. DG is shown in Figure 11 for the MIMO XX and MIMO XY antennas. The simulated DG indicates good improvement in diversity due to the MIMO structures.

2.1. Mathematical modelling of the single antenna

There are two ways of looking at the proposed antenna structure of Figure 1a. The first considers two folded slot antennas. This was
explained before and used for initial prediction of the antenna lengths. The second considers that the antenna structure is based on two dipoles which leads to dual band operation. Regular dipole is directly driven by the CPW feed, while the other dipole is a folded dipole which is parasitically driven, as shown in Figure 12. Regular dipole is designed for a frequency of 38 GHz and the folded dipole is designed for a frequency of 28 GHz.

2.2. Regular dipole

The mathematical modelling of regular dipole is based on the length of the arms of the dipole. The total length, $L$ of the regular dipole arm should be approximately half guided-wavelength of its fundamental mode [30]. The dipole width can be adjusted to tune the input impedance of the antenna to the CPW impedance (see Figure 13).

The total length of the arms of the regular dipole is denoted as $L$. The length $L$ can be calculated using Eq. (4) as [31].

$$L = \frac{0.5 \times c}{f\sqrt{\varepsilon_r}}$$  \hspace{1cm} (4)

The main dipole is designed to resonate at a frequency, $f = 38$ GHz, the dipole length is calculated as $L = 1.2$ mm, and the dipole width, $d = 0.351$ mm is optimized using HFSS.

2.3. Folded dipole

The input impedance of folded dipole (shown in Figure 14) is given by Eq. (5):

$$Z_{in} = \frac{2Z_0[(1+a)^2Z_0]}{2Z_0 + (1+a)^2Z_0}$$  \hspace{1cm} (5)

Where $Z_0$ is the input impedance of strip dipole antenna with length $L$ and width $W_1$ in antenna mode. $Z_0 = jZ_o \tan(k \times L/2)$ is input impedance in transmission line mode where $Z_o$ is the characteristic impedance of the coplanar strip in the homogenous medium of relative permittivity $\varepsilon_r$ as expressed in Eq. (6), $k$ is wave number and $a$ is current division factor [32, 33].
The complete elliptic function of first kind $K(k)$ is approximated by [34] as shown in equation 7

$$K(k) = \left\{ \begin{array}{ll}
\frac{1}{2\pi} \ln \left[ \frac{\sqrt{1 + k} + \sqrt{k}}{\sqrt{1 + k} - \sqrt{k}} \right]; & 1 \leq \frac{K}{\sqrt{2}} \leq \infty, 1 \leq k \leq 1
\\
\frac{2\pi}{\sqrt{1 + k}}; & 0 \leq \frac{K}{\sqrt{2}} \leq 1, 0 \leq k \leq 1
\end{array} \right. $$

Where $k$ and $e$ are calculated using

$$k = \frac{1}{\sqrt{2}} \left[ 1 + e \left( \frac{3}{2} + W_1 \right) \right], \quad e = \frac{W_1 W_2 + \frac{3}{2} (W_1 + W_2) - \sqrt{W_1 W_2 (b + W_1) (b + W_2)}}{\frac{3}{2} W_1 + e \left( \frac{3}{2} \right)}$$

The current division factor for non-uniform dipole radius transformed into equivalent radius for very thin strip dipole can be expressed as Eq. (8).

$$\alpha = \frac{\cosh^{-1} \left( \frac{\nu^2 - u^2 + 1}{2\nu} \right)}{\cosh^{-1} \left( \frac{\nu^2 + u^2 - 1}{2\nu u} \right)}$$

Where $u = W_1/W_2$, and $\nu = 4b/W_2$.

For a frequency of 28 GHz, the folded dipole impedance is calculated to be $Z_0 = 131.8 + \jmath 141.9$ with $\alpha = 0.974$, $u = 1.277$, and $\nu = 22.95$. This results in an equivalent impedance of the complete antenna system (regular dipole and folded dipole) to be $55.347 + \jmath 12.15$, which matches with CPW feedline.

3. Conclusions

Two designs of coplanar waveguide fed slot antenna were proposed. Each design consists of a MIMO dual band antenna operating in the 5G mm frequency range (28 and 38 GHz). The simulated and measured results for the return loss and gain pattern are in good agreement. The simulated ECC indicates low correlation between the antenna elements for both the XX and XY antennas. The group delay is small and increases at the two operating frequencies. The DG has very good performance (close to unity) throughout the frequency band.
Author contribution statement

Amjad Omar: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mousa Hussein: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Indu J. Rajmohan: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Khaled Bathich: Performed the experiments.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Md Nazmul Hasan, Shahid Bashor, Son Chu, Dual band omnidirectional millimeter wave antenna for 5G communications, J. Electromagn. Waves Appl. 33 (2019) 1581–1599.
[2] Mohamed Mamdouh M. Ali, Abdel-Razik Sebak, Dual Band (28/38 GHz) CPW Lost Directive Antenna for Future Cellular Applications, IEEE AP-S, 2016, pp. 399–400.
[3] L. Diouani, A. Diallo, S.M. Farssi, C. Luxey, A novel compact dualband LTE antenna system for MIMO operation, IEEE Trans. Antenn. Propag. 62 (2014) 2291–2296.
[4] Yingying Yang, Quixin Chi, Chuxu Mao, Multiband MIMO antenna for GSM, DCS, and LTE indoor applications, IEEE Antenn. Wireless Propag. Lett. 15 (2016) 1573–1576.
[5] G. Forcini, M. Gans, On limits of wireless communications in a fading environment when using multiple antennas, Wireless Pers. Commun. 6 (1998) 311–335.
[6] W. Hong, K.H. Baek, Y. Lee, Y. Kim, S.T. Ko, Study and prototyping of practically large-scale mmWave antenna systems for 5G cellular devices, IEEE Commun. Mag. 52 (2014) 63–69.
[7] Jun Tao, Quanyuan Feng, Compact ultrawideband MIMO antenna with half slot structure, IEEE Antenn. Wireless Propag. Lett. 16 (2017) 792–795.
[8] M. Prasanna, Design and Analysis of Two Port MIMO Antennas with Wideband Isolation, Master Thesis, National Institute of Technology, Rourkela, 2013.
[9] Shaimaa Ayman Naser, Design and Analysis of Ultra-widband Antennas for Wireless Communications, M.Sc. Thesis, Jordan University of Science and Technology, Irbid, 2015.
[10] J. Abeel, K. Lee, D. Wong, Dual frequency stacked annular ring microstrip antenna, IEEE Trans. Antenn. Propag. 35 (1987) 1281–1285.
[11] H. Akano, K. Vichien, Dual frequency square patch antenna with rectangular notch, Electron. Lett. 25 (1989) 1067–1068.
[12] N. Lopez-Rivera, R. Rodrigues-Solis, Impedance matching technique for microwave folded slot antennas, Proc. Antennas Propag. Soc. Int. Symp. 3 (2002) 16–21.
[13] J. Chen, Dual-frequency slot antenna fed by capacitively coplanar waveguide, Microw. Opt. Technol. Lett. 32 (2002) 452–453.
[14] J. Bennequeeouche, J. Damino, A. Papierk, Original multilayer microstrip disk antenna dual frequency band operation: theory and experiment, Proc. Inst. Electr. Eng. 140 (1993) 441–445.
[15] C.P. Wen, Coplanar waveguide: a surface strip transmission line suitable for nonreciprocal gyromagnetic device applications, IEEE Trans. Microw. Theor. Tech. 17 (1969) 1087–1090.
[16] Amjad A. Omar, Ousama Abu Safa, Mourad Nedil, UWB coplanar waveguide-fed coplanar strips rectangular spiral antenna, RFMCGA 27 (2017).
[17] A.A. Omar, Design of ultra-wideband coplanar waveguide-fed Koch-fractal triangular monopole antenna, RF Microw. Comput. Aided Eng. 33 (2013) 200–207.
[18] A.A. Omar, M.C. Scardellitti, N.I. Dib, R.M. Shubair, Cylindrical CPW fed and CPS fed slot antennas, Int. J. Electron. 96 (2009) 397–407.
[19] A. Omar, Y.M.M. Antar, Design of a dual-band coplanar waveguide-fed slot antenna with wide frequency separation, Int. J. Electron. 88 (2003) 1247–1255.
[20] Amjad A. Omar, Maximilian C. Scardelliti, Zuhair M. Hejaze, Nihad Dib, Design and measurement of self-matched dual frequency coplanar waveguide-fed slot antennas, IEEE Trans. Antenn. Propag. 55 (2007) 223–226.
[21] Wei Hu, Qiani Long, Steven Gao, Le-Hui Wen, Luo Qi, Hang Xu, Xueqiang Liu, Wei Wang, Dual-band eight-element MIMO array using multi-slot decoupling technique for 5G terminals, IEEE Access 7 (2019) 153911–153920.
[22] Naser Gajaoudi Parchini, Yasin I.A. Al-Fariz, Ahmed M. Abdulhakeeq, Haleh Jahanbakhsh Bashlerou, Atta Ullah, Raed A. Abd-Alhameed, A New broadband MIMO antenna system for sub 6 GHz 5G cellular Communications, in: 14th European Conference on Antennas and Propagation in Copenhagen, Denmark, 2020.
[23] Imee Ristika Rahmi Barani, Kin-Lu Wong, Yu-Xuan Zhang, Wei-Yu Li, Low-profile wideband conjoined open-slot antennas fed by grounded coplanar waveguides for 4 × 4 5G MIMO operation, IEEE Trans. Antenn. Propag. 68 (2020) 2664–2675.
[24] Amer Tawfeeq Abel, Aqeel Mahmood Jawad, Compact size MIMO amer fractal slot antenna for 3G, LTE (4G), WLAN, WiMAX, ISM and 5G communications, Progress Electromagn. Res. C 19 (2011) 125542–125551.
[25] M. Sharaawi, Printed Multiband MIMO antenna systems and their performance metrics, IEEE Antenn. Propag. Mag. 55 (2013) 218–232.
[26] A. Najam, Y. Duroc, S. Tejdni, UWB-MIMO antenna with novel stub structure, Progress Electromagn. Res. C 19 (2011) 245–257.
[27] J. Ren, D. Mi, Y. Yin, Compact ultra-wideband MIMO antenna with WLAN/UWB bands coverage, Progress Electromagn. Res. C 50 (2014) 121–129.
[28] IE3D Software of Zeland Inc.
[29] S.S. Jebarng, M.S. Sharaawi, A Single layer semi-ring slot Yagi-like MIMO antenna system with high front-to-back ratio, IEEE Trans. Antenn. Propag. 65 (2017) 927–942.
[30] Antenna Theory: Analysis and Design - Constantine A. Balanis - Google Books. h ttp://books.google.ae/books/about/Antenna_Theory.html?id=v1PS2480mu EC&redir_esc=y. (Accessed 22 July 2020).
[31] M.H. Jamaluddin, M.K.A. Rahim, M.Z.A.A. Aziz, A. Azrok, Microstrip dipole antenna for WLAN application, in: 2005 1st International Conference on Computers, Communications, Signal Processing with Special Track on Biomedical Engineering, 2005, pp. 30–33.
[32] G. Hua, C. Yang, P. Lu, H.-X. Zhou, W. Hong, Microstrip folded dipole antenna for 35 GHz MMW communication, Int. J. Antenn. Propag. 2013 (2013) 1–6.
[33] S. Keyrouz, H.J. Visser, R.J.M. Vullers, A.G. Tijhuis, Novel analytical procedures for folded strip dipole antennas, in: 2012 6th European Conference on Antennas and Propagation (EUCAP), 2012, pp. 2479–2482.
[34] H.J. Visser, Improved design equations for asymmetric coplanar strip folded dipoles on a dielectric slab, in: Second Eur. Conf. Antennas Propag. 2007 EuCAP 2007 11–16 Novemb. 2007 Edinb. UK, pp. 1–6.