3D-Printed mm-Wave Antenna Fabricated using Spray-Coating Technology for 5G Communication Systems

Shaker Alkaraki, Yue Gao, Kin-Fai Tong, Zhinong Ying and Clive Parini

***Abstract*— this paper presents a 3D-printed millimeter-wave antenna for 5G applications. The proposed antenna has a measured bandwidth of 3.6 GHz with a peak measured gain of 7.5 dBi at 28.5 GHz. Furthermore, the antenna is fabricated using simple, yet low cost and novel method utilizes 3D printing and commercial conducive spray-coating technology. The proposed antenna is small, light, compact, and rigid. Besides, it delivers good performance over a wide band which qualifies it to be an excellent candidate for 5G applications.**

***Index Terms* – 3D printed antenna, 28 GHz, 5G, grooves, corrugations, compact, millimetre-wave (mm-wave).**

I. INTRODUCTION

In the past two decades, several technologies have been developed to meet the tremendous growth in cellular data and wireless transmissions. For example, the third generation partner project (3GPP) and different releases of Long Term Evolution (LTE), e.g. 4G, have been released to satisfy this demand [1]. Those releases have used cutting edge techniques to enhance the spectral efficiency and system capacity, such as heterogeneous network, carrier aggregation (CA), coordinated multipoint (CoMP) transmission/reception and multiple input outputs (MIMO) [2]. Nevertheless, current cellular and wireless technologies are not able to handle tremendous rise in the total mobile data traffic by 2020 [3-4], as the global mobile traffic is expected to increase to 30 Exabytes per month in 2020 which is 10 fold increment compared to 2014. In addition, wireless traffic generated by mobile PCs and tablets is expected to grow by 3 fold and 12 fold, as consequence in the growth of mobile phone users which is expected to grow to 9.2 Billion by 2020 [5]. Hence, the unprecedented demand on data transmissions raises challenges for researchers to develop new wireless technology beyond the existing one. Fifth generation (5G) mobile communications technology which is expected to be standardized by 2020 is a promising technology that expected to achieve 1000 times overall system capacity, ten times data rate (i.e. peak data rate of 1 Gb/s for high mobility and 10 Gb/s for low mobility), 25 times average cell throughput, at least 10 times spectral and energy efficiency as well as 5 times lower latency. The main target of 5G technology is to connect the entire world and to achieve extremely reliable, robust and energy efficient communication between anything (machine to machine, people to machine), anybody (person to person), whenever they want and wherever they are [5]-[7]. Yet, 5G technology is not standardized, and several research activities are carried on different technologies works on different frequency bands in a range of frequencies between 5 GHz to 70 GHz [7]-[8]. Furthermore, the 28 GHz band was amongst the highlighted bands above 24 GHz to be used for future mobile communications by the FCC. Therefore, this work presents a design of novel antenna that operates on one of the 5G prominent and potential bands [9]-[10].

The novelty of the proposed antenna relies on different aspects. The 1st aspect is that the antenna is fabricated using simple, yet low cost method utilizes 3D printing and low cost commercial (electromagnetic interference/radio frequency interference)-(EMI/RFI) Shielding Aerosol. To our knowledge, this is the 1st work proposes using the EMI/RFI spray-coating technology for antenna applications. Furthermore, the 2nd aspect of novelty is that the proposed antenna structure with its feeding method is compact and unique as a lot of the state of art 3D-printed antennas relies on replicating the design of conventional and highly efficient non-compact structures such as horn antenna, waveguides and helix antennas and they are usually fed using the highly efficient and reliable standard rectangular waveguide technology [11]-[17]. This is due to the genuine difficulty of integrating as well as matching compact feeding methods with the 3D-printed structures at low and high frequencies. Hence, a lot of the recent 3D-printed antennas are designed and proposed for low frequency applications [12], [16], [18]-[20]. However, in this paper, we present a 3D-printed antenna that has a compact size as well as it delivers a good performance at millimeter-wave, which enables it to be an ideal candidate for 5G applications.

II. ANTENNA STRUCTURE AND FABRICATION METHOD

The schematic and the prototype of the proposed 3D printed millimeter-wave antenna are shown in Fig.1 and Fig.2. The proposed antenna consists of two different structures; the 1st structure is a special feeding layer designed to accommodate the PE 44489 mini-SMP connector and to couple the electromagnetic energy to the radiating structure. The feeding layer consists of transmission line, mini-SMP pad (ground plane) and vias fabricated on Rogers RO4003C substrate. RO4003C is hydrocarbon ceramic laminate which has a dielectric constant of 3.38 and thickness of $h = 0.508\ mm$. The 2nd layer is the radiating structure which consists of 3D printed resonant slot surrounded by rectangular cavity and two corrugations; where the rectangular cavity and the two corrugations boost the antenna gain and directivity. There are two different methods to fabricate the radiating structure; the 1st is to use Computer Numerical Control (CNC) milling machine to perforate the slot and to drill the cavity and the

Shaker Alkaraki, Yue Gao and Clive Parini are with the School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, U.K. (e-mail: s.m.alkaraki, yue.gao , c.g.parini @qmul.ac.uk).
Kin-Fai Tong is with the department of electronic engineering, University College London, London, WC1E 7JE, U.K. (email: k.tong@ucl.ac.uk).
Zhinong Ying is with Sony Mobile Communications, Mobilvägen 1, SE 22188, Lund, Sweden. (email:ying.zhinong@sonymobile.com)

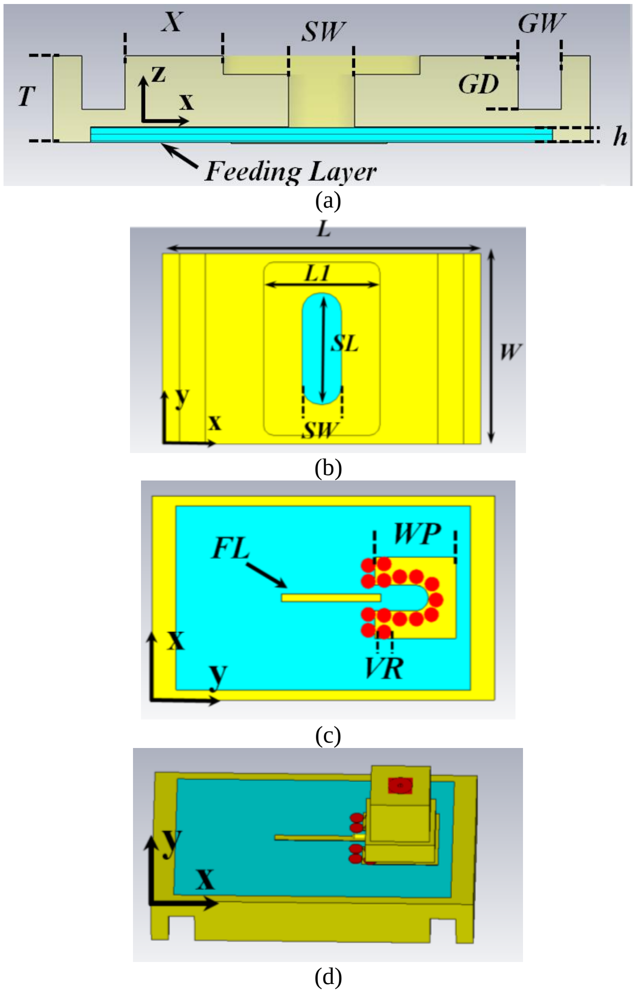


Fig.1. Schematics of the proposed antenna. (a) Cross section of side view, (b) top view, (c) bottom view and (d) perspective bottom view with mini-SMP connector.

corrugations on a metallic plate such as Aluminum [21]. However, the disadvantage of using this method is that it requires highly skilled labour and advanced machinery to realize such small dimensions which boosts the production cost of the antenna.

The 2nd method of the fabrication is to 3D print the radiating structure using a plastic material and then to metalize or plate it with a thin and pure metallic layer; where metals such as Copper, Gold or Aluminum can be used. For the proposed design Objet 30 Prime stereo-lithography 3D-printer is used to 3D print the structure using a transparent verlco-clear material. Furthermore, Object30 3D prints prototypes with a layer thickness of 16 μm and a resolution of $100\mu m$. However, to reduce the cost of production and to reduce the fabrication complexity, commercial conductive paint is used to metalize the 3D printed antenna instead of the conventional metallization techniques. Therefore, the 3D printed antenna is coated using a conductive spray paint contained in air drying acrylic resin. The Aerosol resin dries within 5 minutes after spraying and it delivers maximum conductivity after 24 hrs. The coated and non-coated 3D-printed prototypes are shown in Fig.2. The commercial conductive paint used is RS

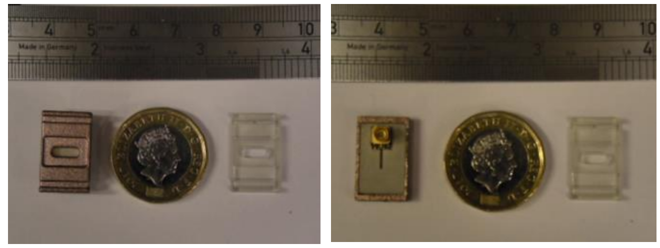


Fig.2. Prototype of the proposed design before and after the spray coating. (a) Top view and (b) bottom view.

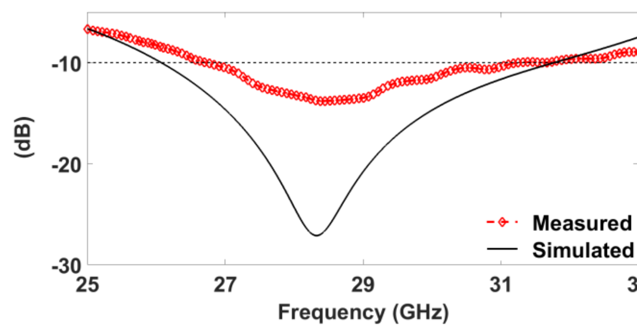


Fig.3. the measured and simulated S_{11} of the proposed antenna.

EMI/RFI Shielding Aerosol that has a Bronze color. According to the manufacturer, the Aerosol is a silver/bronze plated copper shielding paint designed to give low resistance even in thin layers on plastic electronic housing designed for electromagnetic interference/radio-frequency interference (EMI/RFI) shielding applications [22].

The dimensions of the proposed antenna are: length of the antenna $L = 18\,mm$, width of the antenna $W = 10\,mm$, thickness of the antenna $T = 3\,mm$, width of the corrugation $GW = 1.5\,mm$, depth of the corrugation $Gd = 1.9\,mm$, thickness of the substrate $h = 0.508\,mm$, cavity width $W1 = 9.5\,mm$, cavity length $L1 = 7\,mm$, distance between cavity and corrugation $X = 3.2\,mm$, slot width $SW = 2.2\,mm$, slot length $SL = 6.5\,mm$, transmission line width $FW = 0.4\,mm$, transmission line length $FL = 5.4\ mm$, vias diameter $VR = 0.8\ mm$, connector pad width and length $WP\ \times WP\ = 4.4\ mm \times 4.4\ mm$.

III. Results and Analysis

The proposed antenna is modelled and simulated using CST software, where the 3D printed structure is modelled as a PEC. The simulation results shows that the proposed antenna has a -10 dB bandwidth of 5.8 GHz ranges from 26 GHz to 31.8 GHz; however, the measured -10 dB bandwidth of the antenna is 3.7 GHz ranges from 26.9 GHz to 30.6 GHz as shown in Fig.3. Furthermore, the antenna has a simulated peak gain of 9.6 dBi at 29.5 and a simulated gain of 9.4 dBi at 28.5 GHz and generally the simulated gain is higher than 9 dBi over its entire bandwidth. However, the measured peak gain is 7.5 dBi at 28.5 GHz, as well as the antenna has measured gain higher than 7 dBi over 2 GHz, ranges from 27.7 GHz to 29.7 GHz as shown in Fig.4. The simulated and measured far-field radiation patterns of the antenna at 28.5 GHz are shown in

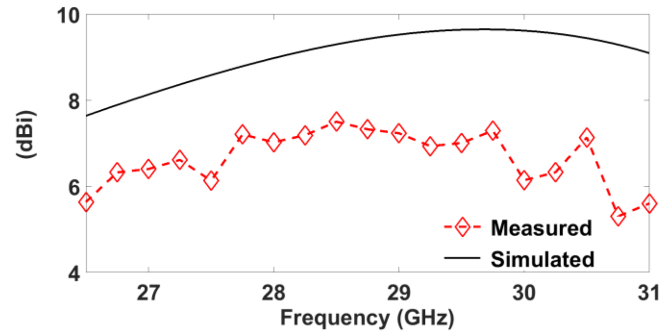


Fig.4. the simulated and measured gain of the proposed antenna over its measured bandwidth.

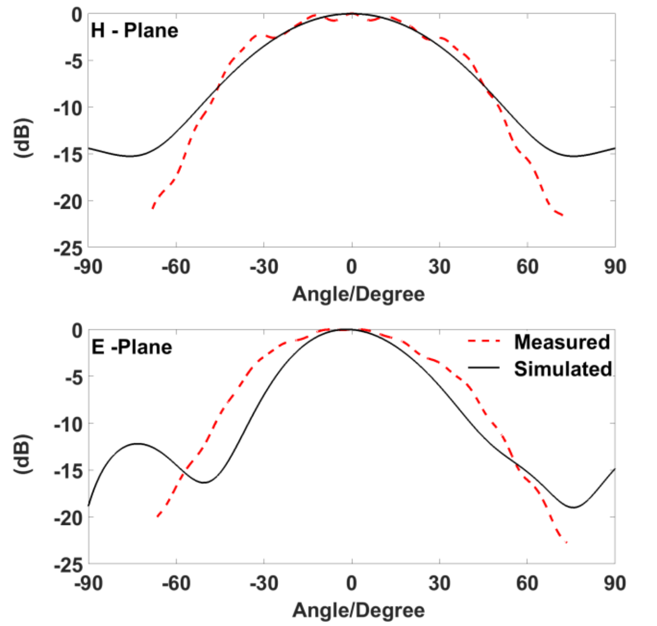


Fig.5. Normalized simulated and measured radiation patterns at 28.5 GHz.

Fig.5. The proposed antenna has a measured half power beam width of 60° in the H-plane and 53° in the E-plane as shown in Fig.5. Moreover, there is a good agreement between the simulated and measured H-planes, while an acceptable agreement is obtained between the simulated and measured E-plane, where the measured beam width is 11° wider than the simulated one. In addition, the proposed antenna has similar measured radiation patterns performance over its bandwidth. Furthermore, the gain of the antenna is measured using gain comparison method described in detail in [24] and by utilizing Ka-band 22240-20 Flann standard horn antenna. However, the radiation patterns were measured using near field scanning method as the energy in the near field is measured and converted by the measurement system to far-field patterns using Fourier transform. The system which has been used to measure the antenna near-field is (200V NSI) available at Queen Mary University of London antenna's laboratory. 200V NSI is a vertical planar scanner, where it has been used with the measurement setup provided in Fig.6. The proposed antenna (AUT) is mounted on top of a stationary holder and the near field probe is moved in both X and Y direction along the surface of the antenna, so that samples of the near-field are measured. For consistent measurements using planar near field

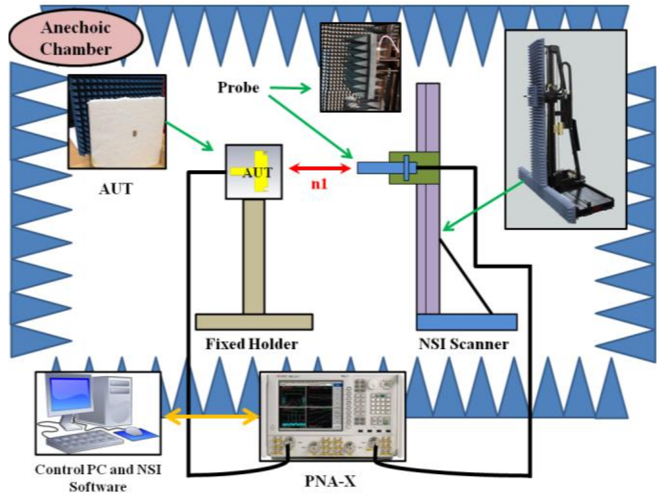
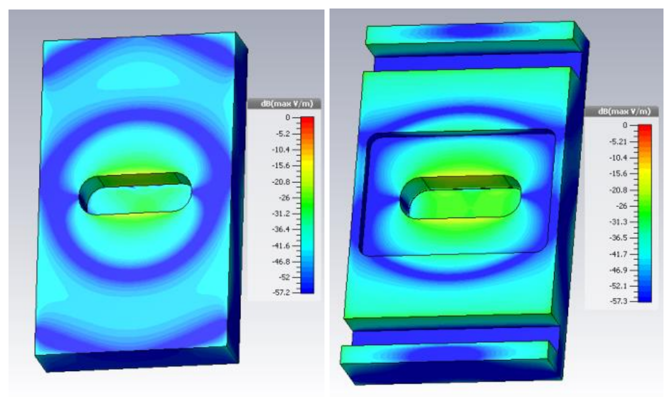


Fig. 6. The measurement setup used to measure the near-field of the proposed antenna. The distance between probe and antenna under test is n1 $= 44\ mm \approx 4.2\lambda$ at 28.5 GHz.



(a) (b)

Fig.7. the simulated electric field (E-field) distribution on the antenna surface at 28.5 GHz. (a) with slot only and (b) with corrugations and cavity.

systems, the separation between the AUT and the probe is recommended to be in range of $3\lambda \leq n1 \leq 5\lambda$ [25]. This separation is chosen to maximize the angular range over which the far-field data is reliable. Hence, planar near field scanners typically provide reliable measurements in a range of $60° \leq \emptyset \leq 70°$ [25]. Finally, the separation between the AUT and probe is chosen to be $44\ mm \approx 4.2\lambda$ at 28.5 GHz.

Overall, the antenna has good measured S_{11}, measured radiation patterns and measured gain performance over wide bandwidth, however, some discrepancies were observed between the simulated and measured values due to several reasons. The 1st reason is because of insertion losses as well as matching losses due to mini-SMP connector soldering and mis-aligning with the 0.4 mm width transmission line. The 2nd reason of discrepancies is the fabrication tolerances of the feeding structure as well as the 3D-printed structure. For instance, one of the limitations of the used 3D printer that it cannot print sharp 90° degrees corners, especially for the corrugations, slot, cavity and at antenna edges. Moreover, the unevenness and surface roughness of the coated antenna after applying the paint affect the radiation patterns of the antenna as well as they contribute to matching losses, especially around the slot area which affect the S_{11} resonance. These uneven and rough surfaces are uncounted for in the simulation process as the slot and the antenna surface were modelled as a PEC with extremely fine and smooth non-lossy surface. Furthermore, the conduction losses of the paint contribute to some of the degradation in the measured gain performance of antenna. For example, according to manufacturer data sheet, the used EMI/RFI aerosol has surface resistivity ranges from 0.3 to 0.77Ω per sq. at 50 μm layer thickness [22]. This certainly will contribute to some conduction losses that affect the gain of the antenna.

In the proposed antenna, the Electromagnetic energy (EM) is coupled via the connector to the transmission line in the feeding structure. Then, the EM energy is coupled from the transmission line to the surface of the 3D-printed structure via the resonance slot as shown in Fig.7. Therefore, the energy is coupled to the surface of the structure in form of a transverse electric (TE) surface wave that is polarized in the x-direction (along SW) and part of this energy is directly radiated via the slot and the rest of it, propagates on the surface of the structure and lost at antenna edges. However, introduction of the cavity and the corrugations excites the surface waves and the combined radiation from the slot, cavity and corrugations is responsible for the gain enhancement [21], [23]. Therefore, the antenna has a gain of 4.9 dBi at 28.5 GHz due to radiation from the slot only. Therefore, introduction of the corrugations and the rectangular cavity on top of the antenna surface improves the antenna gain by 4.7 dBi, as the antenna has a peak simulated gain of 8.7 dBi with corrugations and 9.6 dBi with the corrugations and cavity.

IV. Conclusion

A 3D-printed compact antenna for 5G applications is presented in this paper. The proposed antenna resonates at 28.5 GHz with a measured bandwidth of 3.5 GHz. The antenna structure consists of a feeding layer as well as a 3D-printed radiating structure. In addition, the 3D -printed is metalized by using EMI/RFI shielding conductive aerosol paint. Using EMI/RFI aerosol paint reduces the production cost of the antenna as well as it reduces the complexity of the fabrication procedure, while delivering decent performance suitable for millimeter-wave 5G applications.

References

[1] Y.-H. Nam, B. L. Ng, K. Sayana, Y. Li, J. Zhang, Y. Kim, and J. Lee, "Full-Dimension MIMO (FD-MIMO) for next generation cellular technology," *IEEE Comm. Mag.* , vol. 51, no. 6, pp. 172–179, Jun. 2013.

[2] W. Roh, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, "Millemeter-Wave Baemforming as an Enabling Technology for 5G cellular Communications: Theoretical Feasibility and Prototype Results,*". IEEE Comm. Mag*., vol. 52, no. 2, pp. 106–113, Feb. 2013.

[3] A.L. Swindlehurst, E. Ayanoglu, P. Heydari, and F. Capolino, "Millimeter Wave Massive MIMO: The Next Wireless Revolution,*" IEEE Comm. Mag*., vol. 52, no. 9, pp. 56–62, Sep. 2014.

[4] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!,*". IEEE Access*. , vol. 1, pp. 335–349, May. 2013.

[5] Ericsson.com, "Mobility Report," 2015. [online], available: http://www.ericsson.com/res/docs/2015/ericsson-mobility-report-june-2015.pdf. [Accessed: 27th – Sep - 2017].

[6] C.-X. Wang, F. Haider, X. Gao, X.-H You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, " Millimeter Wave Massive MIMO: The Next Wireless Revolution*". IEEE Comm. Mag*., vol. 52, no. 2, pp. 122–130, Feb. 2014.

[7] Huwei.com, "5G: A Technology Vision," White Paper , 2014.[Online], available: http://www.huawei.com/5gwhitepaper/, [Accessed: 27th – Sep - 2017].

[8] NTT Docomo Inc., "NTT DOCOMO's Views on 5G," Presentation, 2014,available:http://johannesbergsummit.com/wp-content/uploads/sites/6/2013/11/Nakamura-Johnnesberg-Summit-NTT-DOCOMOs-Views-on-5G_rev.pdf [Accessed: 27th – Sep - 2017].

[9] Use of Spectrum Bands above 24 GHz for Mobile Radio Services, GN Docket No. 14-177, Notice of Proposed Rulemaking, 15 FCC Record 138A1 (rel. Oct. 23, 2015).

[10] W. Hong, K.-H. Baek, Y. Lee, Y. Kim, and S.T. Ko, "Study and Prototyping of Practically Large Scale mmWave Antenna Systems for 5G Cellular Devices,". *IEEE Comm. Mag*., vol. 52, no. 9, pp. 63–69, Sep. 2014.

[11] G. P. Le Sage, "3D Printed Waveguide Slot Array Antennas," in *IEEE Access*, vol. 4, no. , pp. 1258-1265, 2016.

[12] M. Kong, G. Shin, S. H. Lee and I. J. Yoon, "Electrically small folded spherical helix antennas using copper strips and 3D printing technology," in *Electronics Letters*, vol. 52, no. 12, pp. 994-996, 6 9 2016.

[13] U. Beaskoetxea, S. Maci, M. Navarro-Cía and M. Beruete, "3-D-Printed 96 GHz Bull's-Eye Antenna With Off-Axis Beaming," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 1, pp. 17-25, Jan. 2017.

[14] K. X. Wang and H. Wong, "A Wideband Millimeter-Wave Circularly Polarized Antenna With 3-D Printed Polarizer," in *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 3, pp. 1038-1046, March 2017.

[15] J. A. Gordon *et al*., "An All-Metal, 3-D-Printed CubeSat Feed Horn: An assessment of performance conducted at 118.7503 GHz using a robotic antenna range.," in *IEEE Antennas and Propagation Magazine*, vol. 59, no. 2, pp. 96-102, April 2017.

[16] Y. Tawk, M. Chahoud, M. Fadous, J. Costantine and C. G. Christodoulou, "The Miniaturization of a Partially 3D Printed Quadrifilar Helix Antenna," in *IEEE Transactions on Antennas and Propagation*, vol. PP, no. 99, pp. 1-1.

[17] C. R. Garcia, R. C. Rumpf, H. H. Tsang and J. H. Barton, "Effects of extreme surface roughness on 3D printed horn antenna," in *Electronics Letters*, vol. 49, no. 12, pp. 734-736, June 6 2013.

[18] Y. Li, C. Wang, H. Yuan, N. Liu, H. Zhao and X. Li, "A 5G MIMO Antenna Manufactured by 3-D Printing Method," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, no. , pp. 657-660, 2017.

[19] S. Jun, B. Sanz-Izquierdo and E. A. Parker, "3D printing technique for the development of non-planar electromagnetic bandgap structures for antenna applications," in *Electronics Letters*, vol. 52, no. 3, pp. 175-176, 2016.

[20] J. J. Adams, S. C. Slimmer, J. A. Lewis and J. T. Bernhard, "3D-printed spherical dipole antenna integrated on small RF node," in *Electronics Letters*, vol. 51, no. 9, pp. 661-662, 4 30 2015.

[21] S. Alkaraki, Y. Gao and C. Parini, "Dual-Layer Corrugated Plate Antenna," in *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2086-2089, 2017.

[22] RS EMI/RFI Shielding Aerosol with Bronze colour 400mL data Sheet , http://docs-europe.electrocomponents.com/webdocs/1583/0900766b8158361e.pdf Accessed: 27th – Sep – 2017].

[23] S. Alkaraki, Yue Gao and C. Parini, "High aperture efficient antenna at Ku band," *2017 International Workshop on Electromagnetics: Applications and Student Innovation Competition*, London, 2017, pp. 60-62.

[24] Constantine A. Balanis,"Antenna Measurement",in Antenna Theory, 3rd ed. Hoboken, New Jersey: John Wiley and Sons, 2005, ch. 17, sec.4.2, pp. 1033-1034.

[25] Stuart Gregson, John McCormick and Clive Parini, "Principles of Planar Near-Field Antenna Measurements". Institution of Engineering and Technology, IET Electromagnetic Waves Series, 2007, Volume 53.