Design and Simulation of a 28 GHz Rectenna for Harvesting Wireless Energy

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***Abstract*— This paper, firstly, describes the design of a rectenna that is capable of operating in the band of 5th Generation (5G). The availability of 5G's systems will create the opportunity to harvest energy everywhere in the network's coverage. Secondly, Millimeter Wave (mmWave) (28 GHz frequency) rectifier has been designed to convert the AC microwave energy to 5V-DC at the output of the rectenna system. The current design describes using an antenna for energy harvesting using Computer Simulation Technology (CST) 2014 and a rectifier circuit using Advance Design System (ADS) 2016. Because of its small size, the rectenna could be used for harvesting energy from nearby sources for charging an implantable sensor battery or for other applications where miniaturization is a design consideration. The obtained microstrip antenna design is achieved with good matching point realizing -17 dB return loss. The designed rectifier circuits achieved 5V-DC at its output.**

Index Terms: **Green 5G energy, Microstrip antenna design, Millimeter Wave (mmWave) rectifier. Wireless energy harvesting.**

I.INTRODUCTION

Power transmission dates back to the early work of Hertz. He used two parabolic antennas for transmitting and receiving electromagnetic energy to realize wireless power transfer (WPT). At the end of the 19th century, Nikola Tesla, a genius in the area of generation and power transmission became interested in wireless power transmission from one place to another without wires. He built a giant coil over which rose a mast of 70 meters with a copper sphere at the end. However, there is no record of how many energy was radiated to the space and whether there was any collected energy at any other place.

In reference [1] H. V. Noble, this time in a laboratory, using two 100 MHz dipoles separated by 8 meters, collected several hundred of watts. With this experiment, he laid the basis for power transfer demonstrations. The modern history of power transmission, as far as microwaves are concerned, not only includes the development of technologies for microwave power transmission (MPT), the approach also includes various applications, whose achievements contributed to the development of new ideas and new technologies.

Recently many authors exerted tremendous efforts in the area of WPT. In reference [2] a hybrid reconfigurable structure of a single feed microstrip patch antenna for future 5G mobile communication applications was demonstrated .The hybridization mechanism is based on frequency, radiation pattern and polarization reconfiguration to capture large amount of energy. In reference [3] a rectenna operating in 5G had been designed. In this work perpendicular input and output microstrip lines were used to minimize coupling, thus minimizing the size of the rectenna circuit. In reference [4] a novel best cooperative mechanism (BCM) for wireless energy harvesting and spectrum sharing in 5G networks was devised. In reference [5] a new cellular communication architecture that integrates energy harvesting technologies and social networking characteristics into device to device (D2D) communications for local data dissemination was proposed.

In this paper the possibility of harvesting wireless energy by antenna device to handle its power to mm Wave rectifier to obtain 5V-DC for charging a low power device, such as a mobile, was investigated.

In the rest of this paper section two tell us about 5Gtechnology and their base station classes. Section three investigates the role of smart antenna in estimation of the direction of the maximum of exploited radiation pattern. Section four reviews wireless power transfer theory. Section five explains WPT system topology and rectenna design. Finally section six summarizes and concludes the paper findings.

II. FIFTH GENERATION (5G) TECHNOLOGY

The current mobile network communication system called 5th Generation 5G, which was already operated in some country, introducing a different era in communication systems. Currently, the state of the art is 4G, which operates in the frequency range of 2 GHz to 8 GHz [6]. 5G, on the other hand, will operate in the frequency range of 600 MHz to 71 GHz (US) [7]. 5G Network will be able to achieve very high data rates depending on the environment and the number of users. This high data rate experienced should be achieved in 95% of the covered location [8]. The network capacity will significantly rise since the 5G spectrum will exploit frequencies in the mm Wave bandwidth. The total estimated new bandwidth for 5G will be 10 GHz [9]. This entire spectrum will provide higher quality of service than that provided by the current 4G network.

A.Base Station Classes

The requirements in this specification apply to Wide Area Base Stations, Medium Range Base Stations and Local AreaBase Stations unless otherwise stated. The associated deployment scenarios for each class are exactly the same for BS with and without connectors [10]

For BS type 1-O and 2-O, BS classes are defined as indicated below:

- Wide Area Base Stations are characterized by requirements derived from Macro Cell scenarios with a BS to UE minimum distance along the ground equal to 35 m.
- Medium Range Base Stations are characterized by requirements derived from Micro Cell scenarios with a BS to UE minimum distance along the ground equal to 5 m.
- Local Area Base Stations are characterized by requirements derived from Pico Cell scenarios with a BS to UE minimum distance along the ground equal to 2 m.

In certain regions, power limits corresponding to BS classes may apply for BS type 2-O. Here in this paper medium range BS type 1-O standard was used.

B.Radiated Transmit Power

BS type 1-H, BS type 1-O and BS type 2-O are declared to support one or more beams, as per manufacturer's declarations specified in[11]. Radiated transmit power is defined as the effective isotropic radiated power (EIRP) level for a declared beam at a specific beam peak direction. For a declared beam and beam direction pair, the rated beam EIRP level is the maximum power that the base station is declared to radiate at the associated beam peak direction during the transmitter ON period.

C. Over The Air (OTA) Base Station Output Power

OTA BS output power is declared as the TRP radiated requirement, with the output power accuracy requirement defined at the radio interface boundary (RIB) during the transmitter ON period. TRP does not change with beamforming settings as long as the beam peak direction is within the OTA peak directions set. Thus the TRP accuracy requirement must be met for any beamforming setting for which the beam peak direction is within the OTA peak directions set.

The BS rated carrier TRP output power shall be within limits as specified in table below:

Table I: BS rated carrier TRP output power limits for BS type 1-O

BS Class	$P_{rated,C,TRP}$
Wide Area BS	There is no upper limit
Medium Range BS	$\leq +47$dBm
Local Area BS	$\leq +33$dBm

D.Maximum Output Power

In term of maximum transmission power of UE in mmWave, Federal Communications Commission (FCC) in US has set the max radiated total EIRP limit for mobile station as 43 dBm, including mobile handset, for mmWave bands from 28 GHz to 39 GHz. The EIRP measurement procedure has been defined in [12].Also, FCC sets the max EIRP limit for transportable station (transmitting equipment that is not intended to be used while in motion, but rather at stationary locations) as 55 dBm.

III.SMART ANTENNA AND MAXIMUM POWER TRANSFER

A great deal of research is being done on the adaptive and direction of arrival (DOA) algorithms for smart-antenna systems [13], [14]. As the number of users and the demand for wireless services increases at an exponential rate, the need for wider coverage area and higher transmission quality rises. Smart-antenna systems provide a solution to this problem [14].

A.Smart-Antenna Systems

These systems can generally be classified as either Switched Beam or Adaptive Array [16], [17], [18].We will be concerned here in adaptive array.

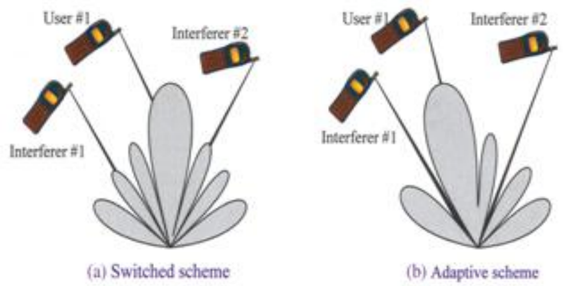

Fig1: Comparison of (a) switched-beam scheme, and (b) adaptive array scheme.

B. Adaptive Array Systems

Adaptive array systems [16], [17] provide more degrees of freedom since they have the ability to adapt in real time the radiation pattern to the RF signal environment. In other words, as shown in Figure: 1(b) they can direct the main beam toward the pilot signal or SOI while suppressing the antenna pattern in the direction of the interferers or SNOIs.

Adaptive array systems can locate and track signals (users and interferers) and dynamically adjust the antenna pattern to enhance reception while minimizing interference using signal processing algorithms. A functional block diagram of such a system is shown in Figure 2

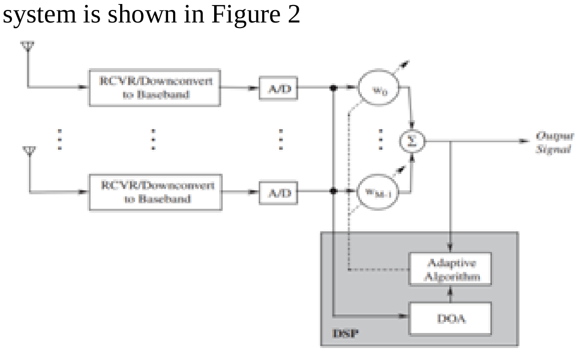

Fig2:Functional Block Diagram of an Adaptive Array System

This figure shows that after the system down converts the received signals to baseband and digitizes them, it locates the SOI using the DOA algorithm, and it continuously tracks the SOI and SNOIs by dynamically changing the weights (amplitudes and phases of the signals). Basically, the DOA computes the direction of arrival of all signals by computing the time delays between the antenna elements, and afterward the adaptive algorithm, using a cost function, computes the appropriate weights that result in an optimum radiation pattern.

C. Antenna Beamforming

The system has gains knowledge from the processed information, and its ability to apply this knowledge. In smart-antenna systems, this knowledge is gained and applied via algorithms processed by a digital signal processor (DSP) as shown in Figure 3. The objectives of a DSP are to estimate

- The DOA of all impinging signals, and

-The appropriate weights to ideally steer the maximum radiation of the antenna pattern toward the SOI and to place nulls toward the SNOI.

IV. WIRLESS POWER TRANSFER

Wireless Power Transfer (WPT) is the transmission of electrical or magnetic energy without the use of wires. WPT is used in cases where the use of wires for powering a device is either not easy or venturesome [19]. In WPT, we have two main techniques for transmission: the near field coupling and far field coupling. In both cases, there is a transmitter, two “antenna devices”, that can be inductors, capacitors, antennas etc. and a rectifier circuit on the receiver side. Below, we briefly describe the far-field technique, which is the one relevant to this work [19], [20].

In far field techniques, power is transmitted through radio waves. Microwave transmission is more directional, giving the capability of transmitting over longer distances. The frequencies used for microwave WPT are between 300MHz to 300GHz, or wavelengths between 1m to 1mm. The system used for the WPT is called a rectenna (“rectifier” and “antenna”). Rectennas convert the AC signal that is received from a dedicated or an ambient source [21]. It consists of three main components: the receiving antenna, the rectifier and a matching network/circuit for matching the antennas and the rectifier's impedances, which is used for maximizing the power transfer or minimizing signal reflection from the load. The distance between the transmitter and the receiver can be from a few Kilometres to many Kilometres, depending on the transmitting power and the application [22], [23].

WPT have many applications one of them is portable rechargeable electronic devices that are used daily could use WPT. Those devices could be cellphones, laptops, tablets, sensors and any small low power device.

V.SYTSEM TOPOLOGY

The rectenna consists of four main components as illustrated in Figure 3. The first component is the antenna, which needs to operate in the operating frequency of interest, in our case $f = 28GHz$. The next component is the matching network that will match the output impedance of the antenna to the rest of the circuit in order to achieve optimal transmission of the signal from the antenna to the load. The next one is the rectifier that consists of a diode that does not transmit frequencies higher than 80GHz it can operate at least in the $Kaband$. Finally, the last part is the DC filter (peak detector).

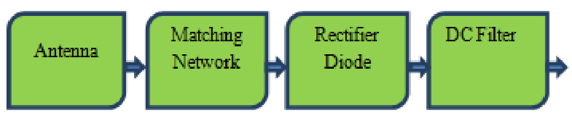

Fig3:Main components of the rectenna.

The proposed rectenna consists of front end which is a 28 GHz microstripantenna, and the other part is ammWave rectifier.

A.5G Antenna

In this design, the channel between BS and capturing microstrip antenna is assumed to be lossless. Complete matching between antenna and rectifier is assumed. Rectangular patch microstrip antennas operating at 28 GHz frequency compatible with 5G mobile technology are designed with Computer Simulation Technology (CST) program for patch material and the performance of the designed antenna.

5th generation mobile technology [24] greatly increases the communication capacity. Performing an antenna with high gain, low loss, low cost, high bandwidth, and high radiation efficiency leads to various design considerations [25]. Modern wireless communication systems require low-profile, lightweight, high-gain and simple-built antennas to ensure reliability, mobility and high efficiency. Therefore, microstrip antennas are highly preferred due to their low profile, simple to manufacture, and ease of feeding.

B. Microstrip Antenna Calculation

A microstrip antenna in its simplest form is a type of antenna with a radiating patch on one side of a dielectric substrate and a ground plane on the other side. For a rectangular patch, the patch length L is generally between λ0/3 and λ0 /2 where λ0 is the wavelength of free space. The patch thickness t is chosen to be very thin such that t << λ0. In general, the substrate height h is 0.003λ0 ≤ h ≤ 0.05λ0. The dielectric constant of the substrate εr is ordinarily in the range of 2.2 to 12 [25].

In order to get efficient radiation, a practical rectangular patch width W can be given as

$$W=\frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (1)$$

Where f_r is the resonant frequency of the antenna, c is the speed of light in vacuum, ε_r is the dielectric constant. The effective dielectric constant of rectangular patch antenna ε_{reff} is expressed as

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{W}}}\right) \qquad (2)$$

where h is the substrate height. Due to the fringing effects, the effective length L_{eff} is obtained as

$$L_{eff}=\frac{c}{2\,f_r\sqrt{\varepsilon_{reff}}} \qquad (3)$$

the actual length of the patch is determined by

$$L = L_{eff} - 2\Delta L \qquad (4)$$

where ΔL is extension length and given by

$$\Delta L= 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.285)\left(\frac{W}{h}+0.8\right)} \qquad (5)$$

In order to operate a microstrip antenna, there are number of feeding techniques. The choice of our design is inset microstripfeed. The input resistance for most typical inset-feed microstrips is given as [25].Feeding technique depends on various factors such as the efficient transfer of power between the radiating structure and feeding structure. Then, the rest of matching conditions can be obtained [26].For inset-feed microstrip patch, notch width g can be formulated as [27].

Lastly, the minimum dimensions of the ground plane,$L_{g_min}$and W_{g_min} can be given as [28].

$$L_{g\_min} = 6h + L \quad (6)$$

$$W_{g\text{-}min} = 6h + W \quad (7)$$

where$L_{g_min}$is the minimum length of the ground plane, $W_{g\text{-}min}$is the minimum width of the ground plane.

C. Simulation Results

In this study, FR-4 with a dielectric constant of 4.3 was selected as a dielectric substrate and its height was 0.1 mm. According to these values and the resonant frequency of 28 GHz, W and L dimensions of the patch obtained from theoretical formulas were approximately 3.29 mm and 2.44 mm, respectively. In designed antenna, inset microstrip feeding was used. The structure of antenna designed by using the CST studio suite2014 is shown in Figure 4. From the formulas above, it was obtained as the inset feeding length,L_d = 0.95 mm, the width of feed length, W_d= 0.194 mm, notch width, g = 0.0174 mm, the minimum dimensions of the ground plane, L_{g_min} = 6 mm and W_{g_min} = 6 mm.

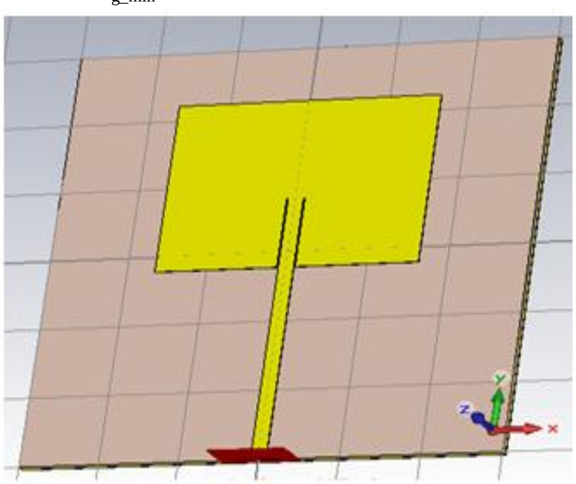

Fig4:The structure of the designed antenna

The design was realized for copper.S-parameter simulation it is most commonly used to characterize a passive MW component and establish the small-signal characteristics of a device Voltage and current are difficult to define and measure in distributed circuits. Incident and reflected waves are the natural description for microwave structures. The return loss graph obtained for this design is shown in Figure 5.

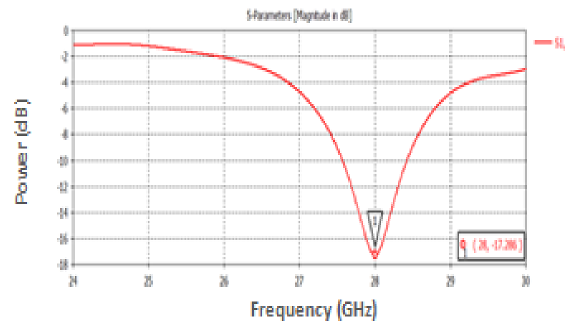

Fig5: The return loss graph for copper conductor

The far-field pattern in 3 dimensional and 2 dimensional (phi=90° and theta=90°) of the antenna designed for patch conductor is presented in Figure 6 and Figure 7 respectively.

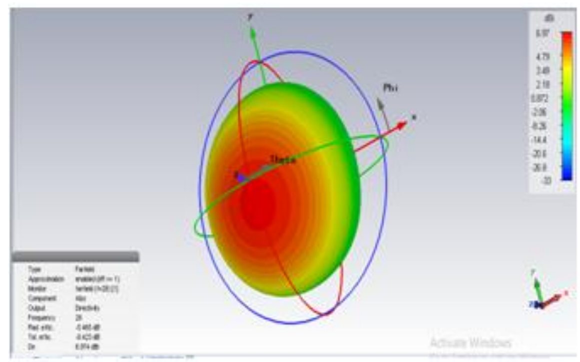

Fig6: The far-field pattern in 3 dimensional of the antenna with copper cladding.

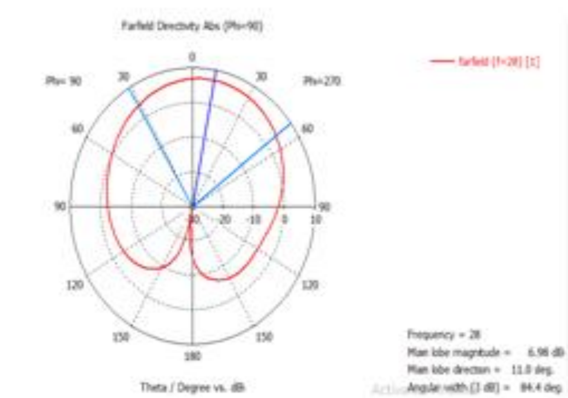

Fig7:The far-field pattern in 2 dimensional (phi=90°) of the antenna with copper cladding.

D. Rectifier Design

A rectifier is an electrical device that converts alternating current AC, which periodically reverses direction, to direct current DC, current that flows in only one direction, in a process known as rectification. Rectifiers have many uses including as components of power supplies and as detectors of radio signals.

The Schottky diode is a semiconductor diode with a low forward voltage drop and a very fast switching action. A Schottky diode is a special kind of diode with a very low forward voltage drop. When current flows through a diode there is a small voltage drop across the diode terminals. A normal silicon diode has between 0.6–1.7 volt drops, while a Schottky diode voltage drop is between approximately 0.15–0.45 volts. This lower voltage drop can provide higher switching speed and better system efficiency we will use disms bas7019930908, provided by Siemens. For rectifier simulations and also each of its components, we have used the Agilent ADS2016 software the schematic view of rectifier circuit is shown in Figure 8.

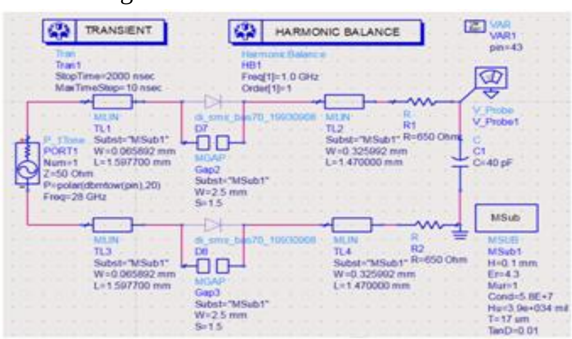

Fig 8: Schematic of double diode rectifying circuit

The rectifier consists of four taperedmicrostrip lines, a double Schottky diode, a λ/4 microstrip line, a Matching microstrip line. The circuit is etched on the substrate of FR4 (εr = 4.3 and h = 0.1mm). The input source of the rectifier was single frequency voltage source. The circuit also consisted of impedance matching network which was in the form of transmission line by defining the width and length. Moreover, the rectifier circuit was simulated by Transient Analysis as shown in Figure 9.

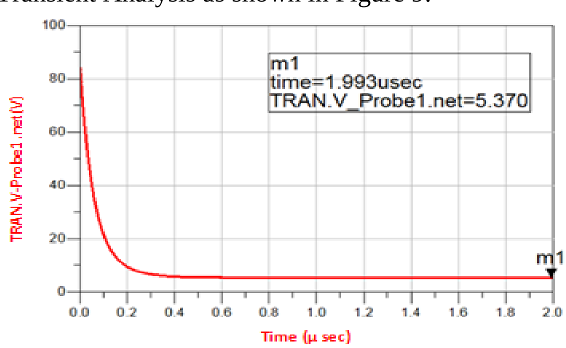

Fig 9:DC output voltage of rectifier circuit

The mobile battery for example for HUAWEI Honor P30 pro plus model is charging by 5 volt DC .This specifications illustrated in [29].The output of designated rectifier circuit on software simulation recorded approximately 5 volt DC as shown in figure 9 and this is our goal.

VI. CONCLUSION

Rectenna design is investigated as wireless energy harvesting device operating at 28 GHz with43dBm. Microstrip patch antenna and rectifier circuit are designed. As a result, the rectenna has a measured output DC voltage is 5.37V such as charger supply. The simulated characteristics of the antenna are analyzed as well but also designing smart antenna using adaptive beamforming algorithm to steer main pattern of receiver antenna to maximum beam of transmitter antenna in order to gain high power as a future work. The antenna measured return loss is also analyzed. Good agreements between the simulated and output voltage of charger to charging battery. At present technical era, we have a very busy schedule. So do not have enough time to be constantly at one place and recharge our electronic gadgets. We not only work at office and home but also work at fields away from power supply. A unique blend of the Rectenna and a sensor circuit in a Mobile phone could provide a new revolution of Mobile Phone charging and will smooth our Lifestyle. This paper showed the successful usage of microwave signals in charging mobile batteries.

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