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Implementation of Brain Computer Interface with RF Power Delivery System

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Abstract: The wireless Brain Computer Interface (BCI) equipped with the Radio Frequency Power Delivery (RFPD) system normally has correct midrange power requirement as well as operating distance ranges for getting powered wirelessly over a long period continuously in order to extend its effectiveness. The BCI is a devic eneeding most importantly, the freedom of movement resulting from this uninterrupted unwired power that does not need any battery replacement or recharging times that can cause distractions of the subject persons, thereby mostly depriving the very purpose of using the BCI. This integrated RFPD system is based on transmission of high power Radio Frequency (RF) waves which is the emerging far field Wireless Power Transfer (WPT) method. This WPT method is having many advantages over other induction and microwave methods because of its safety, non-interference and high efficiency at the medium ranges. The design of all of this BCI system components especially, the low power amplifier and others like RF transceiver, maximum power Tracker and the data transfer protocol are analyzed for optimization of efficient performance for this Electro encephalogram (EEG) based application. The difficulties of integrating and outfitting this BCI with the RFPD system for the effective wireless powered operation is also immensely addressed.

Key words: Brain computer interface, RF, power delivery, wireless power transfer, power harvesting

INTRODUCTION

While there have been many works on RF power harvesting previously as can be seen from the list of references dealing with low power devices (Din *et al*., 2012) wireless sensors (Yeager *et al*., 2008) and both biomedical applications (Rabaey, 2011) specially, EEG (Dementyev and Smith, 2013) and Radio Frequency Identification (RFID) (Monti *et al*., 2012; Ghadimi and Ojaroudi, 2014) along with development of relevant individual components (Costanzo *et al*., 2012) our present research, especially concentrates on EEG based BCI with RF powering that mostly remains so far, not specifically addressed. The brain computer interface many of us know is the input cum output device that gives input to the computer by measuring one's brain waves and gets the desiredoutput according to the intended application. This BCI technology is developing rapidly in recent times due to its vast potential usage. This BCI device, normally operates with medium power, typically having current rating from 10-50 mA at nominal voltage range from 5V down to 1.8 V. They are also mainly operated at the medium wireless distance range of approximately fromaround 1-10 m, i.e., within a large room only.

Figure 1 shows the functional circuit blocks required to be present for the RF power delivery system (Yeager *et al*., 2008; Ouda *et al*., 2013), integrated with that of a typical Wireless BCI device (Rabaey, 2011). The RF transmitter generates and transmits through a large patch antenna, the Radio frequency of 2.45GHz that lies in the unlicensed band used for WLAN or WIFI in most of the countries like US and India. The receiving smaller patch antenna along with its matching circuit and the rectifier cum multiplier called rectenna (RECT ifiyingant ENNA) is responsible for the essential RF to DC voltage conversion at the receiver. Multiple rectennas can also be combinedlike theantenna array for obtaining more receiverpower as explained in (Olgun *et al*., 2011). The power management section consists of the switching regulator for stablesupply voltage generation and the charging circuits needed for the rechargeable battery or the super-capacitor for smooth uninterrupted power (Dementyev and Smith, 2013).

Literature review: Discerning the discrete developments first, the research Umeda *et al*. (2006) presented a 950-MHz wireless power transmission system and a high-sensitivity rectifier circuit for ubiquitous sensor network tags.

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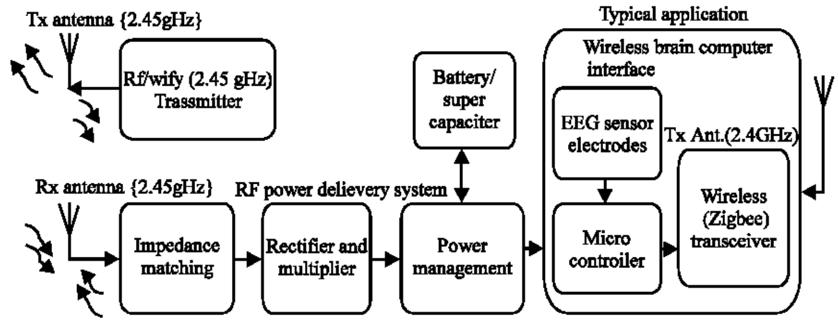

Fig. 1: Simplified Block Diagram of RFPD System and Wireless BCI

The WPT offered a battery-life-free sensor tag by recharging the output power of a base station into a secondary battery implemented within the tag. During the year of 2012, Costanzo *et al.* (2012) presented a new integrated design of RF/Microwave receivers and conversion systems for energy harvesting to be adopted in ultra-low power density environments. Such systems can be very useful in typical humanized scenarios in the presence of existing wireless systems with low power densities. On that same year, Ladan *et al.* (2013) presented an ambient power harvester with high figure of Meritand won in the inaugural student wireless energy harvesting design competition conducted by IEEE Microwave Theory and Techniques Society (MTT-S) International Microwave (IMS2012), the aim of which was to introduce students to the concept and implementation of efficient wireless energy harvester at 900 MHz frequency. Multiple rectenna elements can also be used to generate the dc power for reliable device operation and the research of Digun *et al.* (2011) little earlier in 2011, compared two different rectenna architectures for maximum RF-to-dc power conversion efficiency with a simple rectenna design example containing a 2 by 2 planar antenna array. In 2013, a dual frequency printed dipole rectenna had been developed by Yang *et al.* (2013) for the WPT at dual band of 2.45 and 5.8 GHz using coupling method. GaAs Schottky barrier diode analysis was performed for proper device selection to have high RF-to-dc conversion efficiencies at both frequencies. Chen *et al.* (2013) also reviewed, the development of Ultra Wide Band (UWB) antenna design, another key research area in UWB technology through which a lot of innovative broadband and miniaturization techniques for UWB antennas have been greatly invented and developed for the years. Later in the year of 2014, Chou *et al.* (2014) proposed a high conversion efficiency rectenna for WPT at 2.45 GHz. The rectenna was fabricated on a low-cost FR-4 substrate using dual circularly polarized patch antenna with embedded high order harmonic rejection property and a pair of rectifying circuits without harmonic rejection filters along with the proper management of energy resources essential for any wireless sensing system.

Preferring next the development of low power devices that provide the foundation, the researchers Farinholt *et al.* (2009) early in 2009, presented the use of microwave energy examined as an alternate method for powering compact deployable wireless sensor nodes. A prototype micro strip patch antenna has been designed to operate in the 2.4 GHz ISM band and is used to collect the directed RF energy to power a wireless impedance device that provides active sensing capabilities for structural health monitoring applications. Falkenstein *et al.* (2012) addressed design and implementation of rectifier integrated antenna (rectenna) for WPT at low incident power densities, from 25-200 μW cm^{-1}. Source–pull nonlinear measurement of the rectifying devices is compared to harmonic-balance simulations toobtain optimal diode RF and DC impedances for most efficient rectification, as a function of input power. This allows optimized rectenna design which can eliminate or simplify matching networks and improve overall efficiency. On that same year, Din *et al.* (2012) also presented an RF energy harvesting system that can harvest energy from the ambient surroundings at the downlink RF range of GSM-900 band. Later Scheeler *et al.* (2014) presented research wherein the requirements for the energy harvester are kept stringent with power transmission of 1 μW cm^{-2} incident power density at 2.45 GHz and 915 MHz separately with linear vertical polarization for the wireless sensors to stay powered continuously with power harvesting circuits used for the sensor hardware. Kuntman and Uygur (2013) proposed, an ultra-low voltage, ultra-low power voltage differencing transconductance amplifier with dynamic threshold voltage MOS transistors employed in the design to effectively use the ultra-low supply voltage. Recently in 2015, Chen *et al.* (2013) described a bio potential acquisition system for portable ubiquitous healthcare applications using flexible polydimethylsiloxane dry electrodes and a low power recording circuit.

Analyzing the wireless sensors progress next, itself, Yeager *et al*. (2008) presented the design of wireless Passive Data Logger (PDL) and RFID sensor data logging platform that relies on a new, wirelessly-charged power model which unlike a passive sensor tag is able to collect data while away from an RFID reader. This PDL senses and logs data using energy stored in a capacitor that can be wirelessly recharged and upload the data whenever comes near a reader. Sim *et al*. (2010) presented two compact patch antenna designs for outdoor RF energy harvesting in powering a wireless soil sensor network. The first design is a low-profile Folded Shorted Patch Antenna (FSPA) with a small ground plane and wide impedance bandwidth and the second is a novel FSPA structure with four pairs of slot embedded into its ground plane. Performance of both antennas was simulated using CST microwave studio and then fabricated and tested in the anechoic chamber and outdoor field. The design and implementation of a low power RF harvester for use in smart passive sensor tags applied in structural health monitoring applications is presented by Broutas *et al*. (2012). The tag operation is divided into two cycles namely, a standby mode cycle and a fully operational cycle. While in standby the tag requires only 5 μA at 2.5 V while any excess energy is stored in an accumulation capacitor and made available to the tag during full operation where a low power commercial microcontroller responsible for sensor measurement and data transmission. Vyas *et al*. (2013) designed a unique Embedded Wireless Energy-Harvesting Prototype (E-WEHP) that exploits the unique makeup of ambient digital-TV signals and scavenges wireless power from them at distance of over 6.3 km from the TV broadcast source. The harvested wireless power is successfully used to power and sustain a 16-bit microcontroller for sensing and machine-to-machine applications without the use of batteries. A first fully integrated 5.2-GHz CMOS-based RF power harvester with an on-chip antenna is also presented by Ouda *et al*. (2013) around that time. This design was optimized for sensors implanted inside the eye to wirelessly monitor the intraocular pressure of glaucoma patients.

Referring to biomedical applications during the period around 2011, the exact functioning and operation of the brain has been and still is to a major degree a great mystery. The recent introduction of advanced imaging tools such as fMRI, EEG and eCoG and most recently. This study of Rabuey (2011) explores the opportunities of accomplishing the feasibility of direct neural sensing that throws the doors of neuroscience wide open to enable direct *in-vivo* observations of the brain at work in dynamic conditions and demonstrated just that with a number of examples. Azin *et al*. (2011) described an activity-dependent IntraCortical micro stimulation System-on-Chip (SoC) that converts extracellular neural spikes recorded from one brain region to electrical stimuli delivered to another brain region in real time. etc. described two prototype micro power sensors that potentially help enable neuro prosthetics for the treatment of chronic disease. The first sensor is an EEG instrumentation amplifier for the measurement of neurological field potentials in physiologically relevant bandwidths whereas the second sensor is a three-axis accelerometer for measuring posture, activity and tremor. Both sensor interfaces used dynamic offset cancellation techniques, chopper stabilization for the EEG amplifier, correlated-double-sampling for the accelerometer-to reject low frequency excess noise that might otherwise corrupt the key physiological signals. Also, the website (2015) namely, http://openeeg.sourceforge.net presents the OpenEEG project that has seen contributions from many talented hardware people over the years resulting in several good designs which have been tested and tried by various people.

With regard to EEG developments, Filipe *et al*. (2011) designed a wireless multichannel data acquisition system for EEG recording, based on A Custom Integrated Circuit (ASIC) for signal conditioning, amplification and digitization with commercial components for RF transmission. Dias *et al*. (2012) presented in the next year, a complete non-invasive wireless acquisition system based on dry electrodes for electroencephalograms (WiDE-EEG), composed by a 2.4 GHz RF transceiver, bio potential acquisition electronics and dry electrodes that can acquire EEG signals from 5 unipolar channels with a resolution of 16 bits and minimum analog amplitude of 9.98 μVpp at a sampling rate of 1000 samples/s/channel and sent them to a processing unit through RF in a 10 m range. Next in 2013, Dementyev and Smith (2013) presented an EEG monitoring system that is battery-free, powered by a standard ultra high frequency RFID reader and used backscatter to transmit the data using an EPC-B Class 1 Gen2 protocol as EEGWISP.

Concerning the RFID, Monti *et al*. (2012) presented a rectenna for the harvesting of the microwave energy associated with UHF RFID systems. The proposed device used a capacitive loaded T-shaped monopole with a coplanar waveguide feeding line as receiving antenna and a five-stage voltage multiplier as rectifier. Ghadimi and Ojaroudi (2014) presented an efficient micro strip rectenna operating on ISM band with high harmonic rejection is.

By using rotated E-shaped strip in the radiating patch, a new resonance at lower frequencies (2.4GHz) can be achieved. Also, by embedding cutting a rectangular slot with protruded interdigital strip inside the slot in the feed line a frequency band-stop performance can be achieved. The proposed structure has a major advantage in high harmonic rejection.

MATERIALS AND METHODS

Design of the Bci with Rfpd: Wireless EEG System Powered by a hybrid power supply is already developed by Robinet *et al*. (2011). A battery powered scalable 32-channel wireless neural recording system-on-a-chip for neuroscience Applications is also explained in (Azin *et al*., 2011) wireless BCI device block diagram (Rabaey, 2011) given above in Fig. 1 shows its essential components namely, the low power microcontroller like MSP430 or PIC series, the dry electrodes for sensing and amplifying the EEG signals originating from the scalp and the ZigBee/Wifi/ Bluetooth at 2.45GHz or other RF transceiver such as Zarlink discussed in (Filipe *et al*., 2011) for wirelessly communicating BCI data to the remote computer.

The BCI device components: The wireless BCI devices are now readily availablein different types and we can certainly designgood one, with the supply current requirement in the range from 15-20 mA. At the familiar 3.3V level, the power specification is around 50-100 mW and the corresponding load impedance will be around 200-100 ohms. The own design provides better for efficiency analysis than thewide variety of BCI devices commercially available and the OpenEEGforum is also freely sourcing the hardware details of EEG based BCI along with the necessary source codes for the embedded firmware and the front end Graphical User Interface (GUI) software.

The electrode: The EEG electrodes for BCI are of active type as shown in Fig. 2 preferable to that of passive type and are essentially without gel i.e., dry type as explained in [10], mounted on the rubber belt to be worn around the forehead by the user (Dias *et al*., 2012).

Analog and digital board: The analog board consists of mainly the Amplifier consisting instrumentation amplifier IC TLC272 with active common mode signal rejection is similar to low noise amplifier explained in (Robinet *et al*., 2011). This is standard Current Differencing Transconductance Amplifier (CDTA) an alternative of

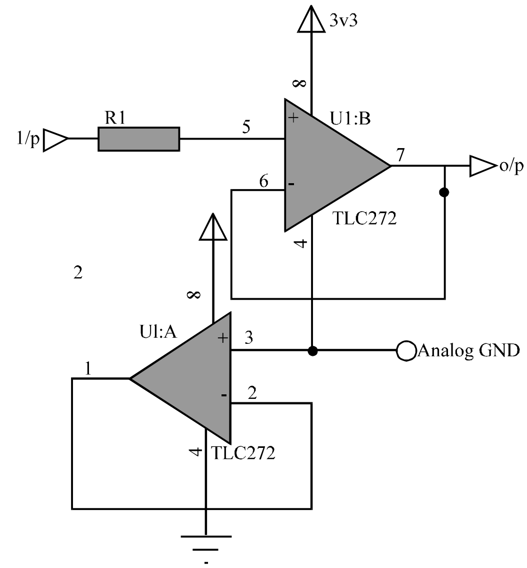

Fig. 2: Active electrode circuit of wireless BCI system

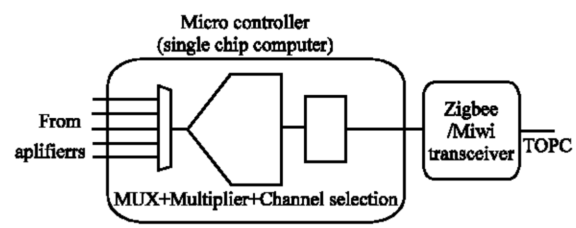

Fig. 3: Block diagram of the BCI digital section

which having the voltages inputs is VDTA canbe used for operation with very low supply voltages consuming power of only, around nanoWatts (2013). The 10 bit analog to digital converter of the micro controller is sampled at approximately 1 KHz by thefirmware and transmitted through the wireless module at optimum 250 kbps as shown in the Fig. 3.

The firmware: The firmware flowchart for the sampling ADC routine is given here in Fig. 4 which is simply implemented using embedded development studio. This BCI is having the Discrete Fourier Transform (DFT) signal processing capabilities to separate, measure and compare the magnitudes of the Alpha (8-13 Hz), Beta (>13 Hz), Theta (3.5-7.5 Hz) and Delta (<3 Hz) wave components of EEG.

D. Software: This data is received by another paired wireless module connected with the serial USB port of the interfacing computer terminal and converted back to the EEG waves by the signal processing Visual Basic software Graphical User Interface (GUI).

The DFT algorithms accurately simulate the necessary low pass, high pass and band pass filter functions and depending on the dominance of alpha over beta or theta wave component's magnitudesthe curser on the user screen is moved to the relevant 'x' or 'y' target direction to indicate visually the level of calmness or activeness in the mind of the user as shown in Fig. 5. This kind of BCI can also be used as gaming tool for a normal person or as mind control trainer for the mentally retarded one.

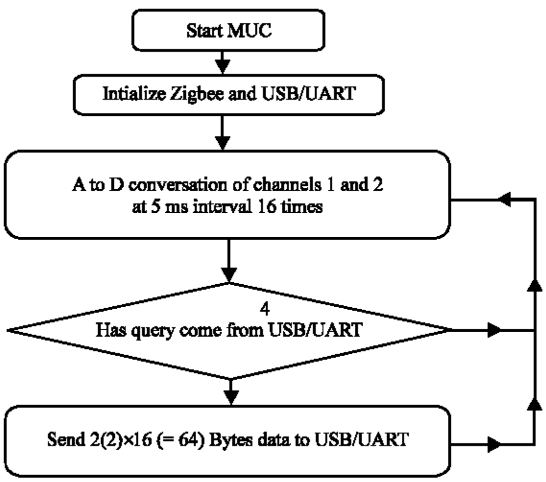

Fig. 4: The simplified bci firmware flow chart

The RFPD system components

Antenna of rectenna: The UHF transmitter with Wi-Fi type antenna transmits the RF waves of 2.45 GHz in the Industrial-Scientific-Medical (ISM) band with the maximum Effective Isotropic Radiated Power (EIRP) of around 3W which is to be harvested with the help of receiver rectenna. The High Frequency Structure Simulator (HFSS) software, the electromagnetics design tool from Ansoft automates geometry creation, solution setup and post-processing reports for thecommon antenna elements. Parameters can be flexibly modifiedin HFSS after generating initial model with required antenna geometry, enabling parametric sweeps for satisfactory optimization. The far-field frequency dependent behavior conveniently provides the effective received EM field of the designed micro-strip E type patch antenna as shown in Fig. 6 along with input impedance i.e., S11 characteristics to effectively maximize the received RF energy at 2.45 GHz.

The rectifier cum multiplier of rectenna: Main parameters influencing efficiency of the diode rectifier deviceand the topology selection are:

- High saturation current (IS)
- Low junction capacitance (CJ)
- Low ideality factor (n)
- Low threshold voltage (Vth)

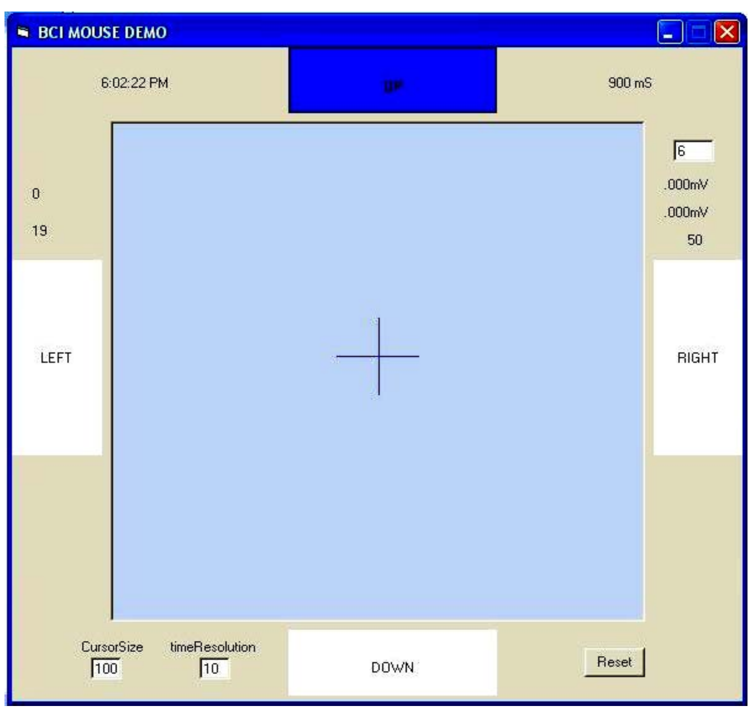

Fig. 5: BCI for directing the cursor to the target side

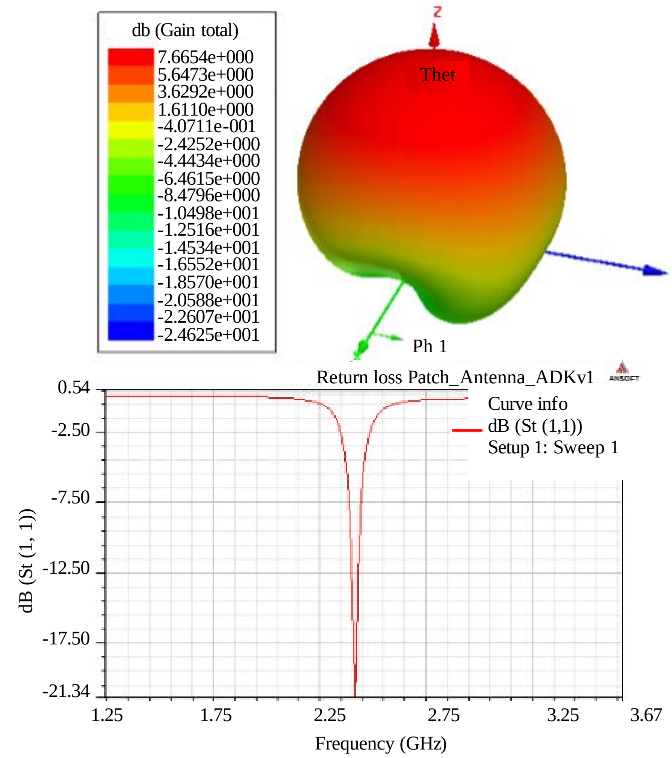

Fig. 6: Far-field patterns and input inpedance; return loss

$$I_D = I_s\left(e^{\alpha d}D - 1\right) \quad (1)$$

Where:

$$\alpha = \frac{q}{nkT}$$

The rectified voltage level is boosted by the Dickson multiplier (Dementyev and Smith, 2013) that is better than Villard multiplier circuit. The output voltage is governed by Eq. 2:

$$V_{out} = 2NV_{in} \quad (2)$$

Where:

- N = The No. of doubler stages involved
- V_{in} = The input voltage made available by the antenna discussed in the previous section

The power management is done by the switching voltage regulator. The DC power is finally smoothened by the ultra-capacitor and delivered to the load, i.e. wireless BCI here. Optional power storage can be provided by Li-Ion battery to reap the advantage of occasional out-of-range operations for brief periods. The rectenna RF to DC conversion efficiency (Chou *et al*., 2014) is given by Eq. 3:

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}} = \eta\left(P_{RF}\right) \quad (3)$$

Where:

- P_{DC} = The DC output power available for the load
- P_{RF} = The RF power supplied by the antenna

The power received by the directive antenna is assessed from the maximum effective area and the directivity (Scheeler *et al*., 2014).

Matching network of rectenna: Referring the RF energy harvesting circuit with on-chip antenna for wireless sensors application discussed in (Ouda *et al*., 2013) the rectification and multiplication are carried out using the Dickson type multiplier involving eight stages, made with the Schottky diodes, MBD7000 is shown in Fig. 7 along with the proper matching network. The results of harmonic balance simulation by Advanced Design Software (ADS) (Falkenstein *et al*., 2012) showing received dc voltages at various stages of multiplier are verified for optimizing efficiency at the operating frequency of 2.45GHz. This design is simpler and more effective here than dual band designs explained in (Scheeler *et al*. 2014; Yang *et al*., 2013) and UWB design discussed (Chen, 2013).

The rectenna prototype: The model rectenna PCB layout designed with proteus design suite shown in Fig. 8 as like the one designed with ADS (Ladan *et al*., 2013) is

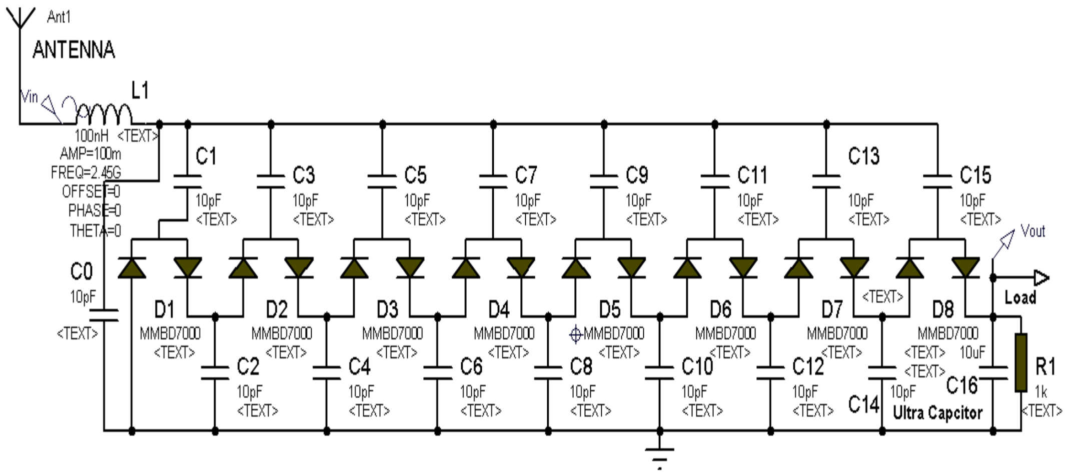

Fig. 7: Dickson type multiplier circuit (n = 8) for harmonic balance simulation

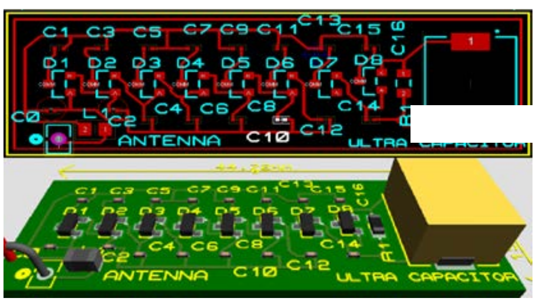

Fig. 8: Front side3D view of the rectenna PCB layout

found to yield better results than the Villard type (Din *et al*., 2012) and the other voltage booster types like Cockcroft-Walton multiplier as explained by Monti *et al*. (2012). There is vast variety of switching regulators available to suit our application and we have chosen TI's TPS series.

RESULTS AND DISCUSSION

Testbed results: The test bench hardware used is constructed with separate controller board and EEG signal amplifier board that has been designed and built as per openEEG resources using low power PIC micro PIC18LF4620, interfaced with the Visual Basic (VB) Dot Net compiled PC software, via the Microchip ZigBee module MRF24WB0MA operating with the maximum transmit current rating of 15 mA as shown in Fig. 9.

Only the ZigBee transceiver firmware for microchip module is additionally included to make its communication wireless. The total power consumption of these boards is 20 mA at 3.3 V or around 75 mW well in

Fig. 9: Test bench wireless BCI system

the middle of our targeted midrange device power from 50-100mW range. The maximum power point tracking is firmware inbuilt feature (Costanzo *et al*., 2012) for increasing the efficiency in power reception.

The coarse working prototype of RF powered wireless BCI system after testing for necessary fine tunings and improvements, sends the filtered EEG signals that are received continuously at the PC. Under ideal conditions, i.e., no reflections and misaligned polarization etc., 15 mW of combined power is likely to be received at 50 cm distance with our transmitting power of 3W at 2.45 GHz frequency, as given in Table 1. For quick comparison, this surely compares well with the efficiency reported in (Vyas *et al*., 2013) example received power of 1.5 mW at 20 cm for a transmission power of 100 mW. The research is still ongoing, to combine more rectenna boards, to attain realistic operating distance of 2 m.

Table 1: Estimated vs. Received power

Transmitted Power (PT, Watts)	Distance (cm)	Estimated power (PA, mW)	Received Power (PR, mW)
3	10	300	240
3	30	33	25
3	50	12	10

Efficiency of RFPD BCI: The working of the antenna both in the receiving or power harvesting mode are verified. The Power received (P_R) by the receiver antenna placed at a distance R from the transmitter antenna can be calculated in free space, from the following Frii's transmission Eq. 4 (Farinholt *et al*., 2009):

$$P_R = P_T\left(\frac{\lambda}{4\pi R}\right)^2 G_T G_R \tag{4}$$

Where:

P_T = The power transmitted

G_T, G_R = The gains of transmitting and receiving antennas, with wavelength of radiation

λ = The c/f at c speed of light and f frequency

Using this Eq. 4 the received power of the patch antenna in free space can be estimated by the process named as link budget calculation.

The transmitters fabricatedare found to perform with comparable efficiency with the readymade available ones, like that from powercast having EIRP of 3W. Refer theexample GHztransmitter design for wireless scavenged Energy presented by Umeda *et al.* (2006). The receiving antenna in our case is the E-shaped patch antenna which yields good performance with the frequency range of 2.40-2.50 GHz as discussed by Ghadimi and Ojaroudi (2014) and though more compact folded patch antenna can also be used (Sim *et al*., 2010). From the practical results shown in above in Table 1, the rectifier efficiency can be tuned by the matching circuit for maximum at the required transmit frequency of 2.45 GHz

CONCLUSION

Thus in this study, we have discussed completely the design of Rectenna based RF powered wireless BCI which is very flexible and easy to use. The integrated improvement works of this wireless BCI system along with RFPD system is getting trimmed and the emerging field test results will then be compared with the final simulations, for future presentations and analysis. We further plan to explore the possibilities of increasing the efficiency of this RF powered BCI by including many distributed RF power transmitters capable of switching with respective RSSI as feedback, thereby also tentatively multiplying the resultant operating distances, even for multiple BCI devices working simultaneously. Similar to the long distance wireless power transmission system using microwaves presented in (Costanzo *et al*., 2012) the future researches can involve the real time simulation and analysis of these BCIs with RFPD system each at considerable distance apart.

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