Demonstration Kit for Battery-Less RF Energy Harvesting Device

Wu Yongxin, Zhang Junwu and See Kye Yak

Abstract Radio Frequency (RF) Wireless Power Transfer (WPT) is a technology that allows devices to be powered wirelessly. This project aims to develop a functional Radio Frequency (RF) energy harvesting demonstration kit, and to assess the feasibility of building a RF energy harvesting kit. The objective of the kit is to harvest and convert RF energy from a transmitter into DC energy to power up a sensor device, or end device. The main focus is on configuring and evaluating the power management circuit and the end device in the kit. The performance of the kit was evaluated. Testing results showed that the demonstration kit was able to power up the end device when RF energy is transmitted to the receiving antenna in the demonstration kit. When the transmitter is placed 94.0 cm away from the receiving antenna, the demonstration kit can be powered up with a minimum power of 21.90 dBm delivered to the transmitter, and the end device can be powered on continuously with a minimum power of 23.30 dBm delivered to the transmitter.

Keywords Radio frequency · Wireless power transfer · Demonstration kit

1 Introduction

Radio Frequency (RF) Wireless Power Transfer (WPT) is a promising technology to prolong the battery life of low-power sensors which is in huge demand in growing sectors such as Internet of Things (IoT). WPT allows devices to be powered wirelessly, and can either be achieved through having a dedicated antenna to transmit

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This project was sponsored by Nanyang Technological University (NTU) as part of the Nanyang Research Programme.

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H. Guo et al. (eds.), *IRC-SET 2018*,
https://doi.org/10.1007/978-981-32-9828-6_16

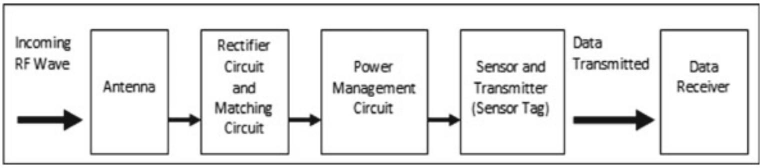


Fig. 1 Overview of demonstration kit components

power, or it can be achieved through harvesting ambient RF energy from existing broadcasting antennas.

The aim of this project is to develop and evaluate a functional RF energy harvesting kit. The kit consists of a rectenna, which comprises a receiving antenna to harvest RF energy and rectifying circuit to rectify and boost the received power to DC, a power management circuit, and the sensor tag which measures the ambient temperature and then sends it wirelessly to a receiver. Figure 1 shows a simple diagram of the demonstration kit.

This project is divided into two parts: The development of the sensor tag and power management circuit.

2 System Setup

As mentioned in the introduction, the demonstration kit comprises of several components shown in Fig. 1. The functions of each component are as follows.

2.1 Receiving Antenna

Firstly, an antenna harvests incoming RF energy. The antenna is comprised of 4 individual patch antennas in an array of 2 by 2. Two antennas are wired in series to form a column, which is then wired in parallel to another column of two antennas in series. This configuration is shown in Fig. 2.

2.2 Rectifier Circuit

The rectifier circuit converts the energy from the antenna into DC current, and boosts the input voltage from the antenna to a level usable by the power management circuit. The rectifiers used are single stage differential Dickson Charge Pumps.

Each antenna is connected to one rectifier, which is then wired in the configuration explained in the antenna section.

Fig. 2 Receiving antenna array and attached rectifier circuit configuration

A matching circuit for the antennas should be used if necessary. The matching circuit should have impedance that is the complex conjugate of the impedance of the antenna, to maximise power transfer from the antenna to the rectifier circuit [1]. A matching circuit was not used for this setup as testing of the antenna found that its impedance is sufficiently negligible.

2.3 Power Management Circuit

The power management circuit manages the DC energy from the rectifier circuit, and provides sufficient and usable energy to the sensor tag for it to operate.

A Texas Instruments BQ25570 Power Management Integrated Circuit is used in this project for this purpose. It manages the power through several functions. Firstly, received DC energy from the rectifier circuit has to be above 330 mV to start charging the storage element during cold start, or above 100 mV to start charging a storage element during continuous operation [2]. Once input voltage exceeds the minimum requirements, the BQ25570 then receives and boosts the input energy's voltage via a boost converter, which is stored within the storage element. A capacitor is used, and the type and capacitance of the capacitor is determined through testing. Once the charged capacitor reaches a sufficient voltage, the BQ25570 allows the storage element to start powering up the sensor tag. A buck converter regulates the voltage of energy from the capacitor if necessary, so as to provide energy with an acceptable voltage to power up the sensor tag.

2.4 Sensor Tag

The sensor tag used is a Texas Instruments eZ430-RF2500. It consists of an end device and access point. The end device uses the energy from the power management circuit to measure the ambient temperature and its input voltage, and then sends the data wirelessly to the access point.

A second eZ430-RF2500 serves as an access point. The access point is attached to a computer and receives the data from the end device, where it is then displayed on screen through the eZ430-RF2500 Sensor Monitor application. In the default factory setting, the access point sends its data to the access point every 1 s. The Sensor Monitor application displays the data from both the end device and access point.

3 Development of Rectenna

The rectenna development is split into two parts. Firstly, the rectifier circuit also has to be optimised to minimise power loss while boosting the voltage of the received power. Secondly, the antenna design has to be selected and optimised to maximise power absorption and efficiency.

The rectifier circuit has to convert the incoming RF energy from the antenna into DC energy, and boost its voltage to a level usable by the power management circuit, which is at least 100 mV when the circuit is in continuous operation. A single stage differential Dickson Charge Pump, shown in Fig. 3, is used for each antenna.

The diodes used must have a low turn on voltage, in order to minimise power loss from the diode and allow the rectifier to rectify input energy with smaller voltages, thus maximizing its efficiency and output. Reference [1] states that a SMS7630 diode is ideal for this application, and is hence used in the rectifier circuit. Reference [1] also mentions that capacitors with a capacitance larger than 10 pF are sufficient for low power rectifier purposes.

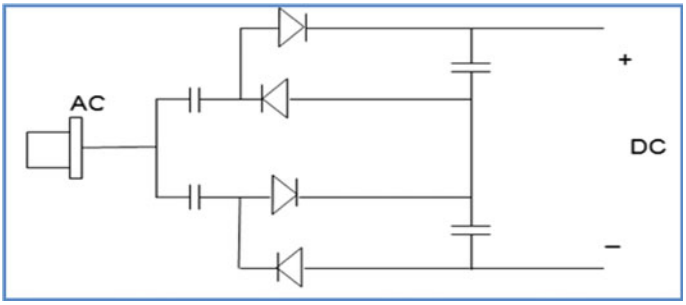


Fig. 3 Single stage differential Dickson charge pump

A square patch antenna is selected for the antenna design due to the ease of fabrication as well as the low profile of the antenna design. These properties allow the antenna to be easily produced, which increases the feasibility of creating the demonstration kit, and also keeps the antenna and subsequently demonstration kit smaller. However, patch antennas have lower efficiency, which necessitates more power transmitted to the antenna to deliver sufficient energy to the power management circuit and power the sensor device [1]. The antenna design was optimised using CST Studio Suite software.

Due to time constraints, optimization of the rectenna was not done. A rectenna provided by the research mentor is used for the final demonstration kit setup.

4 Development of Sensor Tag

The ez430-RF2500 end device needs to operate on energy from the power management circuit and send a signal wirelessly to an access point. To test the functionality of the device, the access point USB is connected to a computer. The end device is then powered up using the provided battery board, and the ez430-RF2500 Sensor Monitor application is run on a computer. Once the end device is connected to the access point, the Sensor Monitor application displays the temperature of both end device and access point, as well as the input voltage of the end device.

The firmware of the end device is edited to reduce its power consumption. Configuration of the end device is done using the source code provided with the ez430-RF2500 Sensor Monitor application, and a compatible code compiler. Code Composer Studio v7 is used for this project and the library rts430.lib is imported from Code Composer Studio v4 for compatibility. The end device code is in the file Main_ED.c. The code is edited to increase the temperature update interval of the end device from 1 to 5 s to reduce power consumption.

This is done by changing the command to measure and send temperature to run only every 5 loops of the end device's inbuilt interrupt function, which is coded to run in 1 s intervals. The following lines of code are edited:

static volatile uint8_t sSelfMeasureSem = 0;
→ static volatile uint8_t sSelfMeasureSem = 4;
if(sSelfMeasureSem); → if(sSelfMeasureSem == 5);
sSelfMeasureSem = 1; → sSelfMeasureSem + +;

The edited code is then compiled, debugged and uploaded to an end device via the USB FET emulator provided. The end device is powered by shorting the jumpers on the battery board, and access point USB stick is connected to a computer. The configured end device now updates its temperature every 5 s on the Sensor Monitor application, while the access point's update interval remains at 1 s. A successfully

```
$HUB0,  30.5C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
$0001,  22.3C,3.0,025,N#
$HUB0,  30.1C,3.6,000,N#
$HUB0,  30.5C,3.6,000,N#
$HUB0,  30.5C,3.6,000,N#
$HUB0,  30.5C,3.6,000,N#
$0001,  22.7C,2.9,025,N#
$HUB0,  30.1C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
$0001,  22.3C,3.0,025,N#
$HUB0,  30.5C,3.6,000,N#
$HUB0,  30.1C,3.6,000,N#
```

Fig. 4 Configured sensor tag readings on sensor monitor application console

edited end device updates once for every 5 updates from the access point, as shown in Fig. 4.

5 Development of Power Management Circuit

To accomplish the function of the BQ25570 as outlined in Chap. 2, the power management circuit is tweaked in three ways.

5.1 Configuration of Jumpers

The appropriate jumpers on the BQ25570 are shorted to enable the desired functions listed above. As stated in [2], the EN pin is connected to GND to enable the integrated circuit. VOUT_EN is connected to BAT_OK to enable the storage element to start and stop powering the sensor tag at VBAT_OK_HYST and VBAT_OK_PROG values respectively.

5.2 Configuration of User Programmable Values

The user programmable VOUT, VBAT_OK_HYST and VBAT_OK_PROG values are configured to a suitable level by changing the resistors on the BQ25570.

The VOUT value is configured to fit within the acceptable input voltage levels of the sensor tag end device. Reference [3] recommends the supply voltage Vcc to the sensor tag during operation to be as follows:

$$1.8\text{V} \leq \text{Vcc} \leq 3.6\,\text{V}.$$

A VOUT value of 3 V, within the recommended range, is chosen for this project. Reference [2] states the VOUT value follows Eq. (1):

$$\mathrm{VOUT} = \mathrm{VBIAS}\left(\frac{\mathrm{ROUT2} + \mathrm{ROUT1}}{\mathrm{ROUT1}}\right). \tag{1}$$

VBIAS is stated in [2] as 1.21 V, as per the BQ25570 electrical specification table. Cross referencing [2] with [4] shows that ROUT1 = R10 and ROUT2 = R9 on the BQ25570.

Substituting the VOUT = 3 V and VBIAS = 1.21 V into Eq. (1) yields the following:

$$3\mathrm{V} = 1.21\mathrm{V}\left(\frac{\mathrm{ROUT2} + \mathrm{ROUT1}}{\mathrm{ROUT1}}\right)$$

$$\mathrm{ROUT2} = \frac{179}{121} ROUTI \tag{2}$$

The recommended operating conditions in [2] states that the resistance sum of ROUT1 and ROUT2 should be as follows:

$$11\mathrm{M}\Omega \leq \mathrm{ROUT1} + \mathrm{ROUT2} \leq 15\mathrm{M}\Omega. \tag{3}$$

Combining the Eqs. (2) and (3) gives the following conditions for the resistors:

$$11\mathrm{M}\Omega \leq \frac{300}{121}\mathrm{ROUT1} \leq 15\mathrm{M}\Omega. \tag{4}$$

The following resistors with 1% tolerance were sourced to configure the VOUT value. Accounting for a 1% error in the resistor value gives the following:

$$\mathrm{ROUT1} = (5.23 \pm 0.05)\mathrm{M}\Omega.$$
$$\mathrm{ROUT2} = (7.68 \pm 0.08)\mathrm{M}\Omega.$$

$$11\mathrm{M}\Omega \leq \mathrm{ROUT} + \mathrm{ROUT2} = (12.91 \pm 0.1)\mathrm{M}\Omega \leq 15\mathrm{M}\Omega.$$

Substituting the above values of ROUT1 and ROUT2 into Eq. (1) yields:

$$\begin{aligned}\mathrm{VOUT} &= 1.21\left(\frac{(5.23 \pm 0.0523) + (7.68 \pm 0.0768)}{(5.23 \pm 0.0523)}\right)\\ &= (2.99 \pm 0.06)\mathrm{V}.(\mathrm{2d.p.})\end{aligned}$$

The VBAT_OK_HYST and VBAT_OK_PROG values should then be configured to allow for a sufficient charge to be stored in the storage element before it is connected to the sensor tag to power it.

Reference [2] states that the VBAT_OK_HYST and VBAT_OK_PROG values follows the equation below:

$$\text{VBAT\_OK\_PROG} = \text{VBIAS}\left(\frac{\text{ROK1} + \text{ROK2}}{\text{ROK1}}\right). \tag{5}$$

$$\text{VBAT\_OK\_HYST} = \text{VBIAS}\left(\frac{\text{ROK1} + \text{ROK2} + \text{ROK3}}{\text{ROK1}}\right). \tag{6}$$

As stated in [2], VBIAS is 1.21 V as per the BQ25570 electrical specification table. Cross referencing [2] with [4] shows that ROK1 = R8, ROK2 = R7 and ROK3 = R6 on the BQ25570. Reference [2] also lists the following conditions:

$$\text{VBAT\_OK\_HYST} \le \text{VBAT\_OV} = 4.2\text{V}.$$
$$\text{VBAT\_OK\_PROG} \ge \text{VBAT\_UV} = 1.95\text{V}.$$

The recommended operating conditions in [2] states that the sum of ROK1, ROK2 and ROK3 should be as follows:

$$11\text{M}\Omega \le \text{ROK1} + \text{ROK2} + \text{ROK3} \le 15\text{M}\Omega. \tag{7}$$

Since VOUT is set at (2.99 ± 0.06)V, VBAT_OK_PROG should be equal to or higher than VOUT. This is to ensure that the voltage output is constant at (2.99 ± 0.06)V, as there is no boost converter between the storage element and output pins to boost the VOUT voltage. A value of VBAT_OK_PROG = 3 V is chosen. The VBAT_OK_HYST value should be high enough to ensure enough energy in the storage element is stored to operate the sensor tag when VBAT discharges from VBAT_OK_HYST to VBAT_OK_PROG. VBAT_OK_HYST is arbitrarily chosen to be 3.6 V. Testing is later done to determine if this value is sufficient and acceptable.

Substituting the VBAT_OK_PROG = 3 V and VBAT_OK_HYST = 3.6 V into Eqs. (5) and (6) respectively yields the following:

$$3\text{V} = 1.21\text{V}\left(\frac{\text{ROK1} + \text{ROK2}}{\text{ROK1}}\right). \tag{8}$$

$$3.6\text{V} = 1.21\text{V}\left(\frac{\text{ROK1} + \text{ROK2} + \text{ROK3}}{\text{ROK1}}\right). \tag{9}$$

Combining the Eqs. (7), (8) and (9) gives the following conditions for the resistors:

$$\text{ROK1} = \frac{121}{179}\text{ROK2} = \frac{121}{60}\text{ROK3}. \tag{10}$$

$$11\text{M}\Omega \le \frac{360}{121}\text{ROK1} \le 15\text{M}\Omega. \tag{11}$$

The following resistors with 1% tolerance were sourced to configure the VOUT value. Accounting for a 1% error in the resistor value gives the following:

$$\begin{aligned}
&\mathrm{ROK1} = (4.3 \pm 0.04)\mathrm{M\Omega}.\\
&\mathrm{ROK2} = (6.34 \pm 0.06)\mathrm{M\Omega}.\\
&\mathrm{ROK3} = (2.15 \pm 0.02)\mathrm{M\Omega}.\\
&11\mathrm{M\Omega} \le \mathrm{ROK1} + \mathrm{ROK2} + \mathrm{ROK3}\\
&\ = (12.79 \pm 0.1)\mathrm{M\Omega} \le 15\mathrm{M\Omega}.
\end{aligned}$$

Substituting the above values of ROK1, ROK2 and ROK3 into Eqs. (5) and (6) yields:

$$\begin{aligned}
\mathrm{VBAT\_OK\_PROG} &= 1.21\left(\frac{(4.3 \pm 0.04) + (6.34 \pm 0.06)}{(4.3 \pm 0.04)}\right)\\
&= (2.99 \pm 0.06)\mathrm{V}.
\end{aligned}$$

$$\begin{aligned}
\mathrm{VBAT\_OK\_HYST} &= 1.21\left(\frac{(4.3 \pm 0.04) + (6.34 \pm 0.06) + (2.15 \pm 0.02)}{(4.3 \pm 0.04)}\right)\\
&= (3.60 \pm 0.1)\mathrm{V}.
\end{aligned}$$

5.3 Selecting a Storage Element

A storage element has to be selected and connected to the VBAT and GND pins on the BQ25570. A capacitor is chosen for the storage element as the increased energy storage capacity of other storage options are not required for this system as both harvested energy and energy consumption of the sensor tag are relatively low. The capacitor chosen should have a low ESR to reduce power loss when charging and a low leakage to reduce voltage loss while the device is being charged or idle. For ease of testing, the capacitor should be easy to connect and disconnect from the BQ25570 setup. Hence through hole capacitors which can be clipped are preferred over surface mounted capacitors that have to be soldered. Lastly, the capacitor should have a maximum voltage that is higher than the VBAT_OV value of 4.2 V, accounting for tolerance. The first capacitor tested is an electrolytic capacitor of capacitance 2200 μF and voltage rating 50 V.

5.4 Optimising the Power Management Circuit

The configured board is connected to a Rohde & Schwarz SMB100A signal generator to simulate power from the rectenna. VOUT, VBAT_OK_HYST and VOUT_OK_PROG values of the board are tested. The signal generator is set at 2.45 GHz to match the antenna in the complete demonstration kit. The power of the

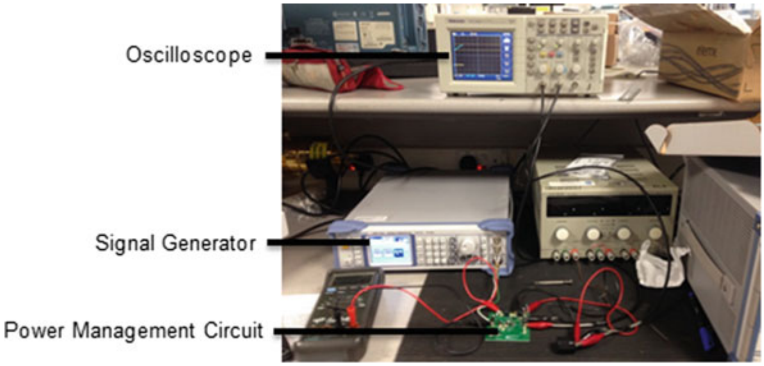


Fig. 5 Setup to evaluate power management circuit

signal generator is set at 6.00 dBm. The rectifier is then connected to VIN and GND of the BQ25570 board to provide power. The capacitor, or storage element, is then connected to VBAT and GND. The voltage levels of VBAT and VOUT are measured using a Tektronix TDS2022 Two-Channel Oscilloscope. The setup is shown in Fig. 5.

When the power source is turned on, VBAT starts rising as the onboard capacitor is charged. Once the voltage of VBAT reaches the programmed VBAT_OK_HYST level of 3.6 V, the output at VOUT is enabled and connected to VBAT. The VOUT voltage should be observed to rise from 0 V to the programmed VOUT level, 2.99 V, once VBAT reaches VBAT_OK_HYST. Further charging of the BQ25570 increases VBAT until it reaches VBAT_OV, after which VBAT is maintained at VBAT_OV.

VOUT rises to 3.04 V when VBAT reaches the VBAT_OK_HYST level of 3.76 V. Further charging increases VBAT until the VBAT_OV value of 4.36 V, after which VBAT is maintained. Figure 6 shows the oscilloscope voltage-time graph of this.

The VOUT value is within the range of the calculated value of (2.99 ± 0.06) V. The recorded VBAT_OK_HYST level is higher than the calculated value of (3.60 ± 0.1) V. This may be due to a faulty resistor or a different VBIAS value from the data

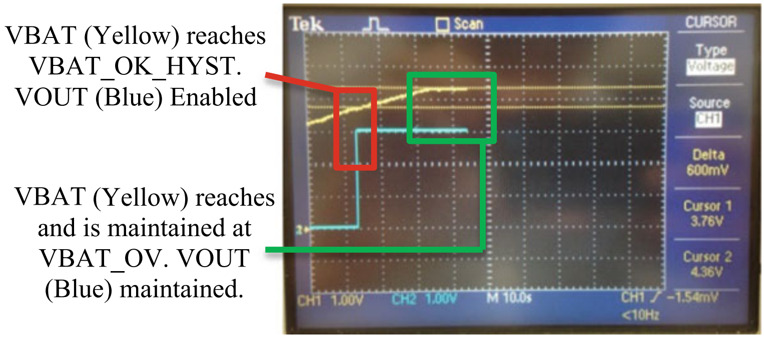
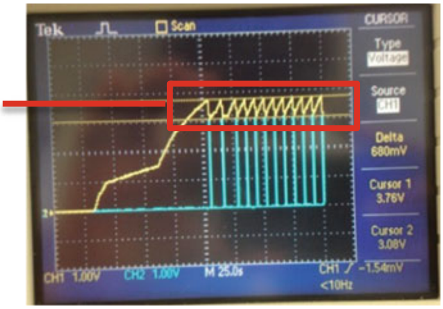


Fig. 6 Oscilloscope voltage-time graph of VOUT and VBAT



VBAT (Yellow) oscillates
between VBAT_OK_HYST
(Upper Cursor) and
VBAT_OK_PROG (Lower
Cursor).
VOUT (Blue) is enabled
briefly when
VBAT_OK_HYST < VBAT
< VBAT_OK_PROG.

Fig. 7 Oscilloscope voltage-time graph of oscillation of VBAT between VBAT_OK_PROG and VBAT_OK_HYST

sheet. As the values are still within a reasonable range from the calculated value, and are well below VBAT_OV, it was deemed acceptable and was not changed.

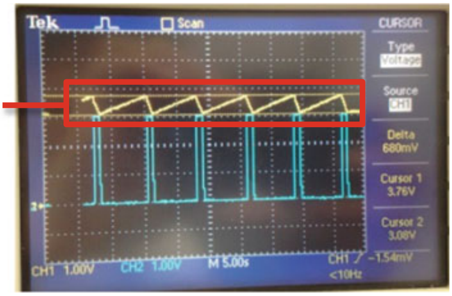
To test the VBAT_OK_PROG value, the input power is turned off or disconnected, and loading is applied to VOUT via resistors connected between VOUT and GND. The resistance values of the resistors are unimportant, as long as it provides sufficient loading on VOUT to decrease the voltage of the capacitor fast. VOUT will be disabled and VOUT value decreases to 0 when VBAT < VBAT_OK_PROG. Once VOUT is disabled, VBAT value should then rise again, if input energy to the BQ25570 is available, until it reaches VBAT_OK_HYST again and VOUT is connected to VBAT. The cycle then repeats itself in the pattern shown in Fig. 7.

The sensor tag end device should then be attached to the BQ25570 to check if the configured values are appropriate and sufficient to successfully power the end device and allow it to send at least one measurement to the access point. The end device's battery board is removed and replaced with wires to allow it to be connected to the BQ25570's output pins.

Once connected, the Sensor Monitor application should be started on a nearby computer with an access point attached. The BQ25570 should be set up in a similar fashion as before, with the addition of the sensor tag end device connected to the VOUT and GND pins on the board. The energy input to the BQ25570 is connected to start charging up the BQ25570 and capacitor. Once VBAT reaches VBAT_OK_HYST, the capacitor starts powering the end device.

As seen in Fig. 8, The BQ25570 and capacitor are unable to provide sufficient energy to start up the end device, and no reading is received and displayed by the Sensor Monitor. The VBAT value alternates between VBAT_OK_HYST and VBAT_OK_PROG as the capacitor is charged up, and then discharged by the end device.

To resolve this, VBAT_OK_HYST may be configured to a higher value, so that the voltage in the capacitor is higher when it starts powering the end device. Alternatively, the capacitor's capacitance can be increased by changing it or adding capacitors in parallel, thus increasing the amount of charge available at the same VBAT_OK_HYST voltage.

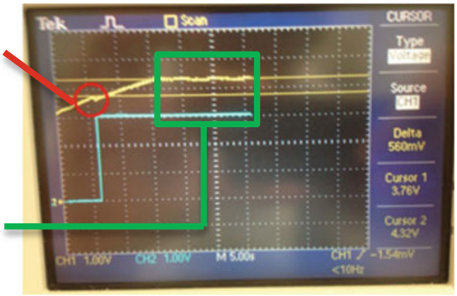


VBAT (Yellow) oscillates between VBAT_OK_HYST (Upper Cursor) and VBAT_OK_PROG (Lower Cursor).
VOUT (Blue) enabled briefly then disabled in a repeating cycle, but is insufficient to power up the end device.

Fig. 8 Oscilloscope voltage-time graph of VBAT and VOUT with end device attached, using 2200 μF capacitor

Configuring the VBAT_OK_HYST value requires new resistors and re-soldering them onto the BQ25570, and is time consuming. Changing the capacitance is hence used.

The capacitance is changed by changing the capacitor to a 4700 μF electrolytic capacitor rated at 16 V. The test is then repeated again to evaluate if the BQ25570 and capacitor is able to power up the sensor tag. Figure 9 shows that the new capacitor contains sufficient charge at VBAT_OK_HYST to power up the end device. There is a short dip of VBAT, indicated by the circle in Fig. 9, due to the end device powering up. Afterwards, VBAT starts rising further as the end device consumes much less energy while running compared to its transient start up power draw. This result indicates that the power management circuit is appropriately configured, and can be assembled with the rest of the demonstration kit.



VBAT (Yellow) reaches VBAT_OK_HYST, slight dip in VBAT when VOUT (Blue) enabled.

VBAT (Yellow) reaches and is maintained at VBAT_OV. VOUT (Blue) Maintained

Fig. 9 Oscilloscope voltage-time graph of VOUT and VBAT with end device attached, using 4700 μF capacitor

6 Demonstration Kit Assembly and Testing

To evaluate the performance of the demonstration kit, the following setup is arranged, as shown in the diagram in Fig. 10.

A Rohde & Schwarz SMB100A Signal Generator is connected to an Amplifier Research Model 40S1G4 Signal Amplifier, which amplifies the signal from the Signal Generator to usable levels. The Signal Amplifier is then connected to an Electro-Metrics EM-6961 1—18 GHz Horn Antenna to serve as the transmitting antenna to transmit RF energy. The receiving antenna, and array of 4 2.45 GHz antennas, is placed 94.0 cm away at an angle of 90°, perpendicular to the transmitting antenna. The rectenna is then connected via crocodile clips to the BQ25570 VIN and GND pins. The BQ25570 is configured as stated in Chap. 5.4 with the 4200 µF capacitor attached. An oscilloscope is used to monitor the voltage of VOUT and VBAT. The sensor tag end device is connected to VOUT and GND of the BQ25570. A computer with an access point USB connected is set up, with the access point being 95.0 cm away from the end device.

To evaluate the operation of the demonstration kit, the signal generator is turned on and its frequency and power level are set at 2.45 GHz and −22.00 dBm respectively. The frequency matches that of the receiving antenna. The signal amplifier is turned on and its gain is set at 100%, which gives a minimum gain of 46.0 dB as stated in [5].

The oscilloscope displays the VBAT and VOUT values of the BQ25570 while being charged. The minimum power required to charge VBAT to VBAT_OK_HYST as well as minimum power required to maintain end device operation at VBAT = VBAT_OK_HYST are recorded. Table 1 shows, for these two conditions, the power output of the signal generator, and the transmitter output which is the signal generator's output boosted by the signal amplifier. The potential difference across the power management circuit's input and GND pins is measured using a multimeter to

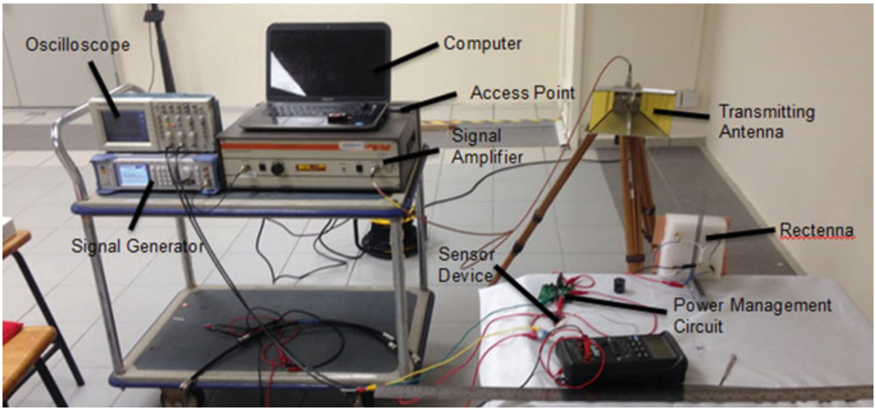


Fig. 10 Picture of actual complete demonstration kit testing setup

Table 1 Results of demonstration kit testing

Conditions	Signal generator power output (dBm)	Transmitter power output (dBm)
Minimum power required to charge VBAT to VBAT_OK_HYST	−24.10	21.90
Minimum power required to maintain end device operation at VBAT = VBAT_OK_HYST	−22.70	23.30

be approximately 0.100 mV at the minimum power required to maintain end device operation.

7 Conclusion

A demonstration kit composed of a receiving antenna, a rectifier circuit, a power management circuit, a sensor tag end device to transmit data, a sensor tag access point to receive data and a sensor monitor application to process and display the data is assembled.

Testing of the setup shows that the kit can operate with a minimum of 21.90 dBm transmitted by a horn antenna from 94.0 cm away, and can power the sensor tag to transmit data. At this level, VBAT levels and continuous sensor tag end device operation can be maintained with 23.30 dBm.

The potential difference of about 100 mV at the minimum transmitted power required to charge kit to VBAT_OK_HYST suggests that the voltage of the energy delivered to the power management circuit input is at the BQ25570's minimum required level. Hence, increasing the input voltage delivered to the power management circuit or decreasing the minimum input voltage requirements of the power management circuit will allow charging of the kit at lower transmitted power levels.

8 Future Work

Based on the performance results of the demonstration kit, the following work is proposed for the demonstration kit:

1. Increase number of stages in the rectifier circuit to increase the voltage delivered to the power management circuit input and allow charging of the circuit at lower transmitted power. Increasing the number of stages will also reduce efficiency of the rectifier circuit due to added components. Hence, testing should be done to

determine the optimum number of stages to decrease the minimum transmitted power required.

2. The power management circuit and storage element may be configured to provide just enough power to power the sensor tag to transmit one measurement before deactivating. The final VBAT_OK_HYST and capacitor capacitance used allows the power management circuit to power the sensor tag for a long time before being discharged. Consequently, however, the storage element takes longer to charge then required if the goal is to enable the sensor tag to transmit once before being disconnected from the storage element.

   The power management circuit itself can be changed from a BQ25570 to a circuit with a lower cold start or continuous operation minimum voltage. This will allow the device to operate off even lower transmitted power levels.

   The storage element can also be changed to reduce ESR and leakage to further reduce power loss and increase efficiency.
3. The Sensor Tag end device firmware can be further edited to reduce the power consumption. The standard end device has a function that waits for an acknowledgement from the access point before sleeping. Disabling this function can reduce power consumption, but will result in the end device not being able to detect if its connection to the access point has been lost, and hence will reduce the robustness of the system. A new sensor tag with even lower power consumption and required input voltage can also be sourced to further increase the efficiency of the system.

Acknowledgements I would like to extend my utmost gratitude to my project mentor, Dr Zhang Jun Wu, for guiding and assisting me throughout every single aspect of the project. I would also like to thank the laboratory technician of the NTU Electronics System Reliability Laboratory, Mr Wee Seng Khoon, for teaching me experimental safety procedures and helping me with various laboratory materials.

I would like to thank my Project Supervisor, Associate Professor See Kye Yak, for accepting me into this NRP Project, and managing the administrative matters for the project. Finally, I would like to thank my NRP Teacher Supervisors Dr Lena Lui and Mr Wong Tze Yang for accepting me into the NRP Programme and handling the administrative matters of the project.

References

1. Wu, Z. J. (2015). *Compact rectenna array on-package for wirelessly powered small device*, PhD thesis, Nanyang Technological University, Singapore.
2. Ultra Low Power Harvester Power Management IC with Boost Charger (Rev. E). (2017). [Online]. Available: http://www.ti.com/lit/ds/symlink/bq25570.pdf.
3. eZ430-RF2500 Development Tool User's Guide, January 2015. [Online]. Available: http://www.ti.com/lit/ug/slau227f/slau227f.pdf. Accessed December 29, 2017.
4. User's Guide for bq25570 Battery Charger Evaluation Module for Energy Harvesting (Rev. A), 2017. [Online]. Available: http://www.ti.com/lit/ug/sluuaa7a/sluuaa7a.pdf.
5. Model 40S1G4 M1 through M4 40 Watts CW 0.7 GHz–4.2 GHz. [Online]. Available: https://www.arworld.us/post/40S1G4.pdf. Accessed January 03, 2018.