The Design of Passive NB-IoT System Based On Wireless Power Transmission Technology

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Abstract. The design of passive NB-IoT system based on wireless power transmission (WPT) technology is presented. The above system consists of a transmitting module and a receiving module. The transmitting subsystem is composed of a microwave power generator and a transmitting antenna. The receiving subsystem is composed of a receiving antenna and a rectifying circuit. In this paper, the voltage conversion, energy storage and power management are realized by using an efficient power management (PM) circuit in the rear stage of the rectifier circuit. It provides 3.6 V to supply the NB-IoT device.

1. Introduction

With the development of the low-power sensor networks, wireless power transmission has become a popular way to power the wireless devices and prolong their life cycles with the dedicated source of microwave radiation [1]– [3]. The wireless RF power transfer has also been recently proposed in the home automation systems [4]. In these applications, the Narrow Band Internet of Things (NB-IoT) is an Internet of Things technology which uploads the data collected by the sensor to the server for analysis and process.

NB-IoT is a new narrowband IoT system built from existing LTE functionalities, which is a long-distance and low-power communication technology [5]. It has the characteristics of wide coverage, low power consumption, low cost and large connection. However, the NB-IoT terminal equipment is usually with a small size and the limited energy in the battery, resulting in a short life of battery. In particular, in some special application environments, such as underground, mountain and forest, it is difficult to replace the battery regularly.

In this paper, a passive NB-IoT system based on wireless energy transmission technology is presented. It realizes voltage conversion, energy storage and power management by using an efficient power management circuit, provided 3.6 V for NB-IoT devices. This paper is organized as follows. Section II presents the theoretical analysis of WPT system. Section III shows the model of power management system. Section IV draws a conclusion.
2. Modeling of WPT system

2.1. Theoretical analysis of WPT system

The geometry of the WPT system is shown in Fig. 1. The system is mainly composed of three parts. The first part is the transmitting module. It converts the direct current (DC) energy into radio frequency (RF) energy, which is mainly composed of the microwave power generator and the transmitting antenna. The second part is microwaves propagation in space. The third part is a receiving module which is a retenna. It receives and converts microwave energy into direct current energy.

During microwave transmission, directional beam is used to keep the beam aligned between transmitting antenna and receiving antenna, and avoid the loss due to beam offset. The microwave power transmission follows the Friis transmission formula and the largest receiving power is

\[ P_{R,MAX} = \left(\frac{\lambda}{4\pi d}\right)^2 P_t G_t G_R = \frac{4\pi A t A r}{\lambda^2 d^2} P_t \]

where \( \lambda \) is the operation wavelength, \( d \) is the transmission distance, \( G_t \) and \( G_r \) are the gains of the transmitting and receiving antennas, respectively. \( A_t \) and \( A_r \) are the effective area, \( P_t \) is the transmission power.

Microwave has the characteristic of strong penetration. It has been proved that microwave beam in space can achieve nearly 100% transmission efficiency in reflected beam wave-guide system. The efficiency of space microwave energy collection \( \eta_c \) is proportional to defined parameter \( \tau \).

\[ \tau = \frac{\sqrt{A_t A_r}}{\lambda d} \]

The efficiency of transmitting module, space and receiving module are RF-DC conversion efficiency \( \eta_g \), free space transmission efficiency \( \eta_t \) and RF-DC conversion efficiency \( \eta_r \), respectively. The total efficiency of proposed system is

\[ \eta = \eta_g \eta_t \eta_r \]

2.2. Rectifier design

The design of the rectifier has been carried out with the aim of achieving the conversion of RF energy to DC electrical energy. The geometry of the rectifier in our design is shown in Fig. 2, which is composed of five parts followed. A band-pass filter rejects all the RF energy except the operating frequency. An impedance matching network delivers the maximum power. A packaged diode performs the RF to DC conversion. A dc-pass filter smooths the ripple of the output DC voltage and a load (NB-IoT Devices).
Fig. 2 The geometry of the proposed rectifier

Schottky diodes are preferred because of the low voltage drop and higher speed. Commercial Schottky diode Bat1503W with $R_s = 5\Omega$, $C_{j0} = 138.5$ fF and $B_v = 6.4$ V is selected and used in this study. The equivalent circuit model of the packaged diode is shown in Fig. 3.

Fig. 3 The equivalent spice model of the selected diode.

The Keysight ADS (Advanced Design System) was used to build the rectifier that was simulated and optimized by using the Harmonic Balance Method. The photograph of the optimized rectifier is shown in Fig.4 shows the comparison between the measurement and simulation. The measured RF to DC conversion efficiency is 72.1% and the DC voltage is 3.96V at the input power of 8dBm.

A good agreement between the simulated and measured results has been achieved. The reason why the measured efficiency and voltage are lower than the simulation is the loss of the diodes and the deviation during the production.

3. Modeling of power management (PM) system

The purpose of the power management (PM) circuit is to realize the voltage conversion, energy storage and power management. Thereby, it provides a suitable and stable voltage to supply the NB-IoT device. The geometry of the proposed PM system in our design is shown in Fig.5. It composed of three parts, energy harvesting circuit, output voltage stabilizing circuit and controlling circuit.
3.1. Analysis of circuit

The energy harvesting circuit harvested the DC energy output from the rectifier circuit, and then performs DC-DC boost conversion to meet the voltage requirements of the subsequent circuit or the energy storage component. In this paper, the BQQ25505 boost charger solution is used to design the energy harvesting circuit.

In order to avoid the damage due to battery overcharge. BQ25505 can use the resistance $R_{ov1}$ and $R_{ov2}$ to configure the overvoltage protection value $VBAT\_OV$. The adjustable voltage range from 1.8 V to 5.5 V. When the input voltage $V_{STOR}$ is higher than the overvoltage protection value, the chip will stop the booster from the working briefly. When $V_{STOR}$ is lower than 24mV, the booster will reboot.

The output voltage stabilizing circuit is used to perform the second DC-DC conversion of the energy of stored component, and provide a stable voltage to the load (NB-IoT devices). A load switch is designed at the output port of the voltage regulator circuit. The controlling circuit dominates the load switch to turn the output power rail on or off. A first DC-DC boost converter is added between the super capacitor and the load. In the case of a super capacitor at low voltage, the system can still output a stable voltage that satisfies the normal operation of the load.

The load switch is a power PMOS. When the PMOS is turned on, its channel resistance is lower than 1 Ω and the cut-off leakage current is below 1μA. For the stringent power requirements of this system, a PMOS with a 920mΩ on-off leakage current of 50nA is selected as the load switch. In this paper, the TPS61099 synchronous booster solution is used to design the output voltage stabilizing circuit.
TPS61099 adopt the synchronous rectification and DC-DC boost voltage structure. The output voltage is depends on the R1 and R2 of negative feedback network. The calculation formula is as follows:

\[ V_{OUT} = V_{REF} \frac{R_1 + R_2}{R_2} \]  

(4)

The controlling circuit acquires the input voltage and the energy storage element voltage from the PM system through the ADC. Where P3.6 is the inlet of input sampled ADC1, P4.3 is the inlet of storage voltage sampled ADC2. It controls the mode switching of the energy harvesting circuit.

3.2. Simulation and measurement results

In order to observe the progress of the boosting process, the super capacitor is replaced with a normal capacitor of 680μF. Fig. 9 shows the waveform of charging test circuit. And the VIN is the input voltage, the VBAT is the storage voltage. When the VIN is about 330mV, the storage voltage can gradually rise to 3.6V.
Fig. 9 (a) The charging test circuit, (b) The waveform of charging test.

Fig. 10 (a) The measurement of DC-DC conversion efficiency (b) The total efficiency of PM.
A second DC-DC converter is between the DC power output and the load. The DC voltage stabilizer RIGOL DP832 and the electronic load are used in the charging test. By measure the voltage and the current of input and output port, the charging efficiency is calculated.

The measurement result of charging test is shown in Figure 10. Due to the two-stage DC-DC conversion circuit, the conversion efficiency is approximately the product of the pre-stage conversion efficiency and the post-stage conversion efficiency. So the overall input-output efficiency is relatively low. In the case of 1 mA input current, the input voltage is needed to be above 1.2V to meet the efficiency requirement of 60%.

The photograph of the NB-IoT system based on WPT technology is shown in Fig.11. The distance between the transmitting subsystem and the receiving subsystem is 1 m. After testing, the whole system output a 3.6V voltage to supply the NB-IoT device.

4. Conclusion
A passive NB-IoT system based on wireless power transmission has been introduced in this paper. A PM system is utilized to achieve voltage conversion, energy storage and power management. The total system can stably generate 3.6 V operating voltage and supply power to NB-IoT devices.

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