Design of Multi-channel Rectifier with High PCE for Ambient RF Energy Harvesting

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***Abstract-* An efficient and successful multi-channel rectifier for ambient RF energy harvesting has been designed and evaluated at GSM-1800 and UTMS-2100 bands. This design could sufficiently enhance the RF-to-DC power conversion efficiency (PCE) in weak signal reception environment. The validity of the proposed design is verified by detailed experimental results, which indicate that a maximum PEC of 38.8% and an output DC voltage of 280 mV have been observed over an optimized 6400Ω resistive load by collecting relatively low ambient RF power.**

I. INTRODUCTION

Recently, there is a growing interest in wireless power transmission (WPT) technology [1] which is in the forefront of electronic development. The main function of WPT is to allow electrical devices to be continuously charged without the constraint of a power cord. Meanwhile, with the rapid development of commercial communication services, the environment of our modern society is full of radio energy that can be recycled. Therefore, radio frequency (RF) energy harvesting, which is considered as a green and efficient power solution in the future, has rapidly become a hot spot of research. One of its most attractive applications is the self-powered devices and systems, which are of immediate significance to solve the battery recharging and replacement issues. There is no doubt that the ambient RF energy harvesting is provided with wide space and opportunities for development, but at the same time, it will also face two practical difficulties. Firstly, the power level of the ambient RF energy available through public telecommunication services is relatively low [1]. Secondly, due to the character of rectifier circuit using physical diode components, the less input RF power, the less RF-to-dc power conversion efficiency (PCE) will be achieved [2]. Therefore, such a weak ambient RF energy will lead to a low RF-to-dc PCE, which makes the RF energy harvesting become dispensable. Unfortunately, currently, various methods presented under large RF input power condition [3, 4] are not suitable to deal with these two problems.

In this paper, we propose a novel multi-band rectifier to solve these problems. This multi-band rectifier can make the best use of the ambient RF energy of each signal channel so as to accumulate the RF power into a sufficiently higher power level, where the power conversion efficiency could also reach a considerable value. The detailed design and experimental results have been presented in the following sections.

II. AMBIENT RF POWER MEASUREMENT

As mentioned above, the environment is full of radio energy that can be used for daily recycled. Therefore, in order to make the best use of these ambient RF energy in each channel, the power densities of ambient RF energy available through public telecommunication services have been investigated by a wide-band horn antenna (ANT-DR18S) and spectrum analyzer (Agilent 8565EC). Measurements are made on the roof of engineering building of national university of Singapore (NUS), which simply represents the residential environment in urban area of Singapore. The related power densities are calculated then from Friis transmission equation, as shown in Table I. From the measurement results, it is clear that only down-link channels in three bands, GSM-900, GSM-1800 and UTMS-2100, dominant the ambient RF energy since powers from base-stations are more persistent and stable than powers from portable devices.

TABLE I
TYPE SIZES FOR PAPERSAMBIENT POWER DENSITY OF EACH SINGLE CHANNEL OF DIFFERENT PUBIC TELECOMMUNICATION BANDS (MEASURED BY HORN ANTENNA)

Band	Downlink Frequency (MHz)	Received Power (dBm)	Antenna Gain (dBi)	Power Density ($\mu W / m^2$)
GSM-900	925-960	-35 ~ -25	2	23.8 ~ 256.7
GSM-1800	1805-1880	-25 ~ -15	10	143.9~ 1560.6
UTMS-2100	2110-2170	-25 ~ -15	10	196.6~ 2079.2

Meanwhile, the total RF power of all ambient communication bands that the horn antenna received is measured by power meter and it varies from -20 to -15 dBm (10 ~ 31.6 μW). It also could be found in Table I that the power densities of GSM-1800 and UTMS-2100 bands are obviously much larger than that of GSM-900 band. Therefore, with the consideration of the physical size of the final RF energy harvesting system, the following multi-channel rectifier in the paper has been designed to cover only GSM-1800 and UTMS-2100 bands.

III. MULTI-CHANNEL RECTIFIER DESIGN

As the input RF power is relatively low (< -10dBm), the series-diode rectifying topology has been adopted in this design as it could achieve a higher efficiency under such a condition [2]. Figure 1 shows the maximum RF-to-dc power conversion efficiency that this series-diode topology structure can achieve. This figure is simulated by with practical components (HSMS-2852 and PCB RO4003C) in ADS. It can be seen from Figure 1, when power level is low (< -20dBm), efficiency increases significantly as power increases as mentioned previously.

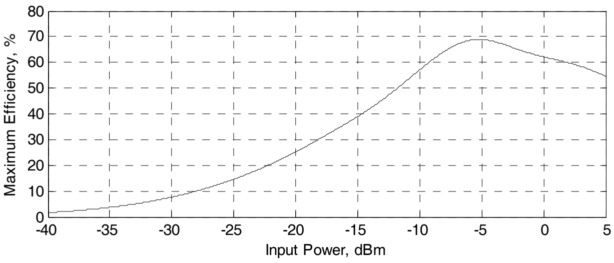

Figure 1.Maximum RF-to-dc power conversion efficiency in series diode topology (Diode: HSMS-2852, PCB: RO4003C)

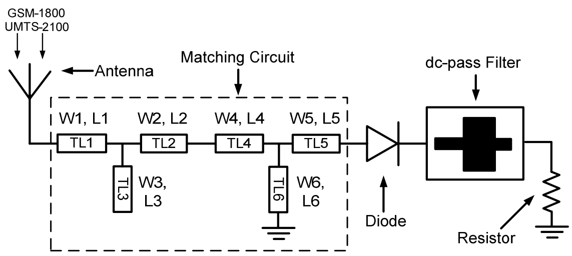

Figure 2.Topology of the proposed rectifier.

The entire topology of the proposed rectifier is illustrated in Figure 2. The substrate used is 32-mil-thick RO4003C with dielectric constant of 3.38. As mentioned before, in this design, the series-mounted diode topology is adopted since it tends to have a higher efficiency under low input RF power conditions. From [5], dual-frequency impedance matching can be achieved by a signal T-shape transmission line structure. However, this method can match at only two single frequency points. Therefore, to increase the bandwidth of our wide-channel rectifier, two T-shape microstrip-line structures have been adopted in this circuit, which are shown as TL1 to TL6. To provide a dc-patch in the circuit, the microstrip line TL6 is grounded by via-holes. A Schottky diode Avago HSMS-2852 (V_{th} = 150 mV, C_j = 0.18 pF, R_s = 25 Ω) is inserted between the matching circuit and the dc-pass filter to convert the microwave power into dc power. The dc-pass filter is realized by a simple stepped-impedance microstrip line low-pass filer, followed by a resistive load to extract the dc power. To further reducing the parasitic effect of lumped components, a cross-shape microstrip-line structure has been introduced into this circuit design to replace the traditional lumped capacitor components,

The parameters of the matching circuit, dc-pass filter and the resistive load can be initially calculated and then optimized in the software Advanced Design System (ADS) by setting appropriate goals. At the first stage, a preliminary rectifier containing only a diode, a dc-pass filter, and a resistor, was optimized under low input power with the goal of high efficiency at both 1.84 GHz and 2.14 GHz. In this way, the optimal dc-pass filter and the load resistance was obtained. After that, the matching circuit was optimized separately to match the input impedance of the rectifier to 50 Ω at both 1.84 GHz and 2.14 GHz. The optimized parameters are (unit: millimeter): W1 = W2 = W3 = 2.2, L1 = 7.8, L2 = 19.9, L3 = 10.4, W4 = W5 = W6 =2.7, L4 = 12.5, L5 = 9.3, L6 = 10.8. The load resistance is optimized as 6.4kΩ. Figure 3 shows the photograph of the fabricated rectifier.

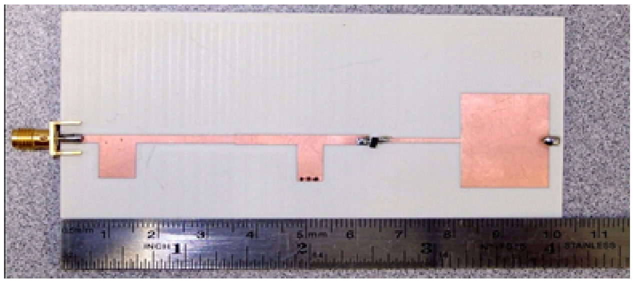

Figure 3.Photograph of the fabricated dual-band rectifier.

IV. MEASUREMENT RESULTS

To verify the frequency-power related performance of our multi-channel rectifier, its single-tone RF-to-dc power conversion efficiency performance has been tested first. A signal generator (Agilent E8257D) is used to generate this single-tone input signal. Figure 4 shows the measured PCE against frequency at different power levels (-30dBm to -18dBm). The measured conversion efficiency can be obtained by equation (1),

$$\eta(\%) = \frac{V_L^2}{R_L} \times \frac{1}{P_{in}} \times 100 \quad (1)$$

where V_L is the output dc voltage on the resistor, R_L is the resistance value, and P_{in} is the power level of the single-tone input signal generated by a signal generator. It can be seen from Figure 4 that higher efficiencies can be achieved in the frequency ranges of 1.81-1.87 GHz and 2.11-2.17 GHz, which demonstrates a good agreement with the initial objective, revealing the rectifier's capability to harvest the RF power in the GSM-1900 and UMTS-2100 bands. Meanwhile, it can be seen from the figure that when several channels in either band are activated, the power of these channels can be conversed at the same time at a high efficiency. In fact, the input power to the rectifier can be regarded as multi-tone when measuring in the ambience since the ambient RF power is distributed over the two bands.

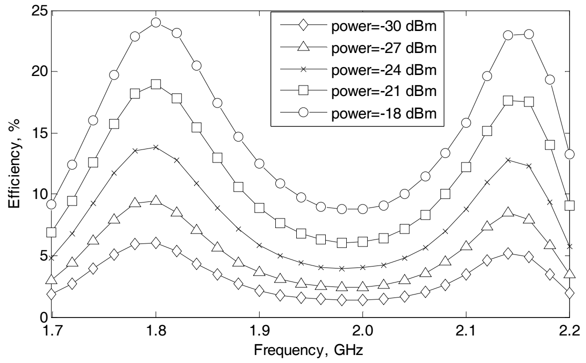

Figure 4.Measured conversion efficiencies at different frequencies

To further validate the efficiency enhancement of this multi-channel rectifier, its two-tone RF-to-DC PCE performance has also been explored. With the help of two Agilent E8257D signal generators and a power splitter (ZFRSC-42), the measured PCE against each single and dual-tone input power has been measured and plotted in Figure 4. The input signals frequencies are 1.80 GHz and 2.14 GHz, respectively, which are two of the major frequencies of the two bands. In this experiment, the input power of these two frequencies keeps the same for simplicity. As the ambient RF power is relatively low, -30dBm input has been taken for example to discuss the efficiency enhancement. It can be seen from Figure 5, when input power is -30dBm, the RF-to-dc PEC is only 5.29% and 4.79% for 1.83GHz and 2.14GHz, respectively. However, the same two-tone input RF signal can lead to a higher PCE of this multi-channel rectifier to 11.65%, which is more than twice of each single-tone input situation. It is clear to prove that an addition of input RF signals at different frequencies will help generate a high conversion dc power and a higher efficiency. Hence, this fact implies that through this multi-channel rectifier, dispersed RF powers that are separated in different channels can be harvested at the same time with a considerable higher RF-to-dc PCE.

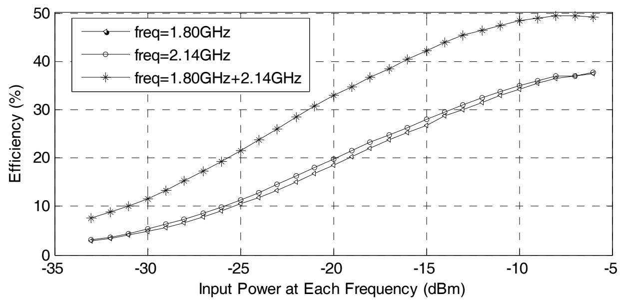

Figure 5.Measured conversion efficiency at different input power levels

Last but not least, this multi-channel rectifier has been connected to the same horn antenna (ANT-DR18S) to test its ambient RF energy harvesting capability. In this experiment, the maximum output dc voltage of the rectifier is above 280 mV when the received RF power varies from -20 to -15 dBm. The PCE of this multi-channel rectenna can be derived according to the maximum input power (-15dBm, 0.032mW), which is above 38.8% for ambient RF energy harvesting. For a clear comparison, the PCE enhancement of this multi-channel rectifier has been listed in Table II.

TABLE II
COMPARISON OF RF-TO-DC PCE FOR SINGLE-TONE, DUAL-TONE AND MULTI-CHANNEL RF ENERGY HARVESTING

Frequency Band	Received Power (dBm)	PCE (%)
Single tone (1.80 GHz)	-30	5.6
Dual tone (1.80 & 2.14)	-30	12.3
GSM-1800 & UTMS-2100	-20 ~ -15	>38.7

V. CONCLUSION

In this paper, a multi-channel rectifier suitable for urban area telecommunication RF power harvesting is proposed. While the RF power at each single channel is relatively low but there are several channels active at the same time, this rectifier can harvest these dispensable RF powers that are separated in different channels together with a considerable higher RF-to-dc PCE above 38.8% when the total ambient RF energy is less than -15dBm. This multi-channel power collection method is suitable for urban area telecommunication RF power harvesting. While the RF power at each single channel is relatively low but there are several channels active at the same time, this multi-channel system can harvest these dispensable RF powers that are separated in different channels together with a considerable higher RF-to-dc PCE compared with these traditional RF energy harvesting system. Since the ambient RF energy harvesting is emerged as an urgent and challengeable issue in the creation of wireless sensor networks which depend on truly autonomous devices, this study can be treated as a very pointed attempt in this respect.

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