Recent Advances in Broadband Rectennas for Wireless Power Transfer and Ambient RF Energy Harvesting

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***Abstract*— Wireless energy harvesting (WEH) from ambient electromagnetic fields is becoming an emerging technology that can be exploited as a power source for many low power electronic devices. A number of key challenges are identified but the optimum design of rectennas for ambient WEH is very challenging. This paper presents a review on recent progress in multiband and broadband rectennas for WEH and wireless power transfer applications, and introduces the latest research on this topic at the University of Liverpool, UK. In addition to the existing technologies, we have developed a number of novel techniques to develop rectennas with a simple structure, a very broad bandwidth and an improved RF-DC conversion efficiency. Moreover, our rectennas can achieve consistent performance for a dynamic input power level or a wide load impedance range. The state-of-the-art technologies presented in this paper could have a great impact on the future development of rectennas for many related applications.**

Index Terms*— Broadband rectennas, multiband rectennas, high efficiency, wireless power transfer, RF energy harvesting.

I. INTRODUCTION

SINCE Tesla's first wireless power transmission (WPT) experiment in the 1890s, transferring energy from a power source to a load without the connection of electrical conductors has attracted a lot of interest over the past century [1]. In 1963, long distance wireless power transmission via microwave was first demonstrated at the Raytheon's Spencer laboratory where 100 W DC power was delivered [2]. One year later, William C. Brown *et al*. demonstrated a microwave-powered helicopter in flight 60 ft above a transmitting antenna [3]. In 2007, a group at the Massachusetts Institute of Technology demonstrated a new approach for transmitting energy over larger distances using resonant inductive coupling, providing 60 W to a lamp placed 2 m from the transmitter with an efficiency of 40% [4]. These significant milestones and successful achievements have motivated the research of WPT, which includes inductive power transfer (IPT) and radiative microwave power transfer over a frequency range from several kHz to GHz or even up to THz. The development of WPT is of great significance to the modern industry, since a range of potential applications have been found in such as wireless communications, sensor networks, RFID, Machine-to-Machine (M2M), and Internet of Things (IoT) [5].

In addition to the aforementioned WPT technologies that normally deliver the power from a predetermined source to a load. In the recent years, wireless energy harvesting (WEH) from ambient electromagnetic fields has been developed where the energy can be obtained directly from wireless signals in the air, such as the mobile, DTV, and WiFi signals [6]. It sounds like a great idea if we could use this technology to replace the battery for many electronic devices. But, some major challenges have been identified when the WEH was used in practice, which include the relatively low power level (e.g., < -30 dBm) and the instabilities in the ambient environment (e.g., multi-path propagation effects). Therefore, the available DC power obtained from real ambience is normally very small while the output power level is consequently very unstable [7].

Multiband and broadband rectennas could be a promising solution to overcome this challenges, since the ambient wireless signals are distributed over a wide frequency band (from 200 MHz to 4 GHz) [8]. Such rectennas can accumulate more energy from different channels and different sources simultaneously and thus produce a higher DC output power. But, due to the nonlinearity of the rectenna, the design of broadband or multiband rectennas is very challenging, while its performance can be easily affected by the variations in such as the input power level and the load impedance. So far, there are very few multiband or broadband rectennas reported with good performance. A need exists for rectennas with high conversion efficiency, a wide frequency bandwidth and also consistent performance in different operating conditions.

In this paper, we firstly present an overview of recent progress in multiband and broadband rectennas for WEH and WPT applications from the literature (in Section II). Then, we introduce a number of new technologies developed by us to design broadband rectennas for WEH and maintain their performance in a varying operating condition (in Section III). We have significantly improved the overall conversion efficiency and the total output power of broadband rectennas, especially when the input power to the rectifier is relatively low (e.g., -30 dBm). In addition, a novel technique to eliminate the complex impedance matching networks for broadband rectennas is presented. The proposed broadband rectenna without a matching network still remains high conversion efficiency and consistent performance..

II. Recent Advances in Rectennas for WPT and WEH Applications

A. Multiband Rectennas

Multiband rectennas have been developed for WEH in the literature [9]–[15]. They normally have high RF-DC conversion efficiency at different frequency bands with a narrow fractional bandwidth (e.g., < 5%). Such rectennas are therefore suitable for energy harvesting from narrowband signals (such as GSM1800, UTMS2100, and WiFi) and they can produce a higher output power than that from single narrow band rectennas. A dual-band rectenna covers 1.8 GHz and 2.2 GHz was reported in [9] with a maximum conversion efficiency of 55%, the output power from this rectenna was about 28 μW for a low input power level of -15 dBm. Similarly, another dual-band design was reported with a maximum conversion efficiency of 50% and a DC output power about 17 μW at the same power level (-15 dBm) [10].

In [9]-[11], the dual-band matching networks were all designed on a single circuit branch and configured with a single rectifier. However, it would be very challenging to design a single branch matching network to cover more than three frequency bands. Thus in [12], the rectenna with a single branch four-band matching network could have a lower conversion efficiency (e.g., < 40%) and thus result in a smaller output power. In [13] and [14], a new idea that configures the rectifiers on different branches was proposed. Each branch had a single-band rectifier for different frequencies. The DC power from the rectifiers was combined at the output. As a consequence, the rectenna designs using such a method can cover more frequency bands and achieve higher conversion efficiency (e.g., up to 84%).

Some designs have developed techniques (such as the resistance compression network) to reduce the nonlinear effects of the rectenna [15]–[17]. In this way, the sensitivity of the rectifier can be reduced where its high conversion efficiency is maintained over a range of load impedance or input power levels. The multiband rectennas with high conversion efficiency and consistent performance would offer significant advantages in ambient WEH applications.

Thus in [18], we reported a novel impedance matching technique for multiband rectennas. In addition to the traditional LC lumped elements for impedance matching against the frequency, a special section formed by microstrip lines was added to the matching network with the aim to improve the matching performance versus a varying load. The complete matching network was divided in three branches. Each branch has a dual-band matching network using the same topology but different component values for different frequency bands. The rectifier covered six different frequency bands (from 550 to 2450 MHz) for the first time, as well as achieved a nearly constant RF-DC conversion efficiency over a very wide load impedance range from 10 kΩ to 80 kΩ. The maximum conversion efficiency was up to 80%. The receiving antenna in this design was a compact ultra-wideband dual circular polarization (CP) antenna with a frequency bandwidth from 500 MHz to 2.5 GHz (almost covers the entire DTV, mobile, WiFi, and ISM bands in the world). The random polarization receiving capability (dual CP) of this antenna helped to obtain more RF power from the ambient environment. The complete rectenna was demonstrated to have the ability to harvest about 96 μW DC power when the input power level was -15 dBm (the highest power in the literature under the same condition). More importantly, the rectenna has a consistent performance for a range of operating conditions such as multiple frequency bands, different input power levels and a wide range of load impedance. The nonlinear effects have been significantly reduced thus it is very suitable for ambient WEH used in practice.

B. Broadband Rectennas

Broadband rectenna designs are even more difficult than the multiband designs due to the nonlinearity of the rectifier. It is very challenging to maintain high conversion efficiency over a wide frequency band as well as a varying condition as mentioned earlier. Therefore, one of the earliest broadband rectennas obtained a relatively low conversion efficiency (e.g., < 20%) over its wide frequency bandwidth (2 – 6 GHz) [19]. Some broadband rectennas have achieved a higher conversion efficiency (e.g., > 60%) [20]– [22], but the input power levels of interest of these designs are relatively high (e.g., 20 dBm) which is not realistic in ambient WEH applications. At relatively low ambient power levels (e.g., -20 dBm), the conversion efficiency of a broadband rectenna can be as low as 10% [23]. Moreover, the design of impedance matching network for broadband rectennas is more difficult than that of other rectennas. The structure of the network is normally very complex. Although there have been many challenges in broadband rectenna designs, it is still worth to research on this topic since the broadband rectennas can significantly improve the output power when the ambient wireless signals have a broad spectrum (i.e., DTV, LTE700 and GSM900 signals from 470 to 950 MHz).

In [24], we presented a broadband rectenna with relatively high efficiency while the rectenna was optimized for very low input power levels (thus suitable for ambient WEH). A special crossed dipole receiving antenna was designed and the harmonic rejection property was embedded. The antenna can receive random incoming waves with arbitrary polarization (thus higher input RF power), and it can also block the higher harmonic signals generated from the rectifier to improve the overall conversion efficiency. The rectifier was designed using a novel two branch broadband matching network and a modified Greinacher circuit. It was optimized to a range of low input power levels, from -35 dBm to -10 dBm.

Consequently, the complete rectenna was of high RF-DC conversion efficiency (e.g., 55% at -10 dBm input power) over a wide frequency range from 1.8 to 2.5 GHz. This broadband rectenna has been demonstrated for harvesting energy from ambient mobile and WiFi signals in a typical indoor office environment. A 2 × 2 rectenna array based on this design was proposed in [25] that combines the DC powers from each single rectenna element. It was found that the output DC power from this rectenna array for ambient WEH was about 15 µW. Thus it could be used to power some devices which require a very small power (e.g., digital clock). This design has successfully demonstrated that it is possible to obtain energy from a typical low-input power ambient environment using broadband rectennas.

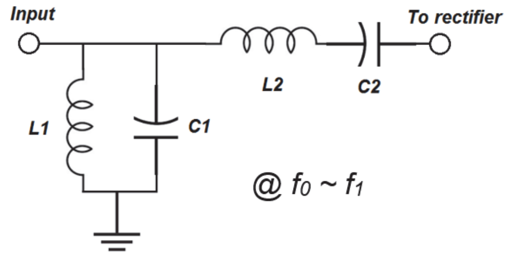

Fig. 1. Conventional LC impedance matching network for a frequency band from 450 to 900 MHz.

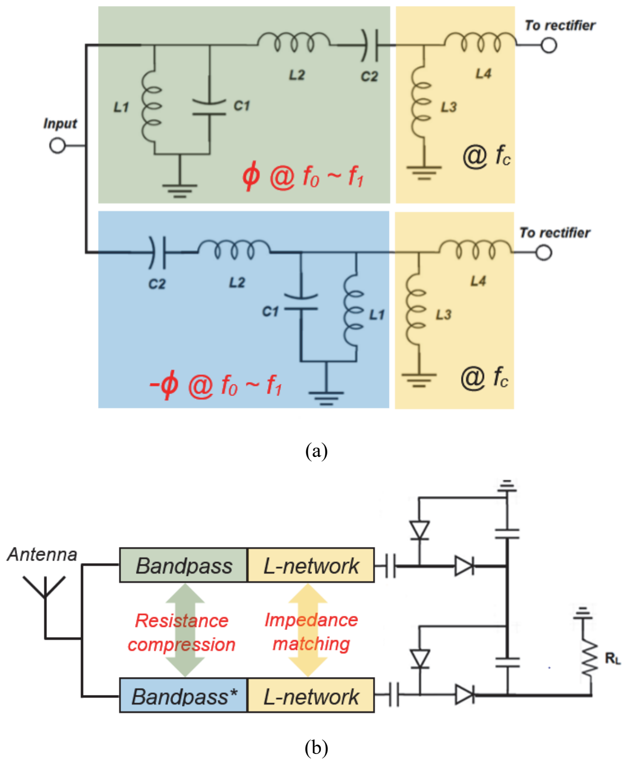

Fig. 2 (a). The broadband matching network using the hybrid resistance compression technique. (b). Configuration of the rectenna using the proposed matching network.

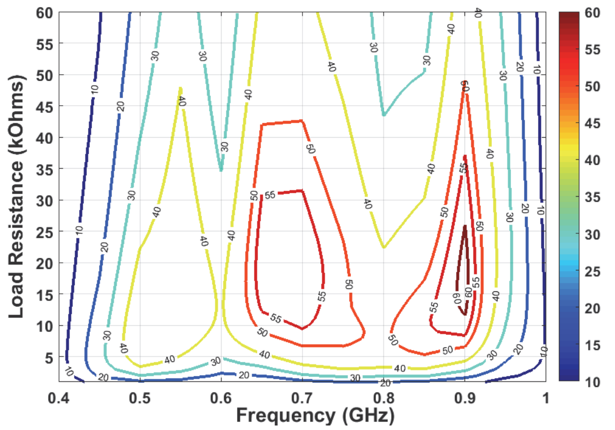

Fig. 3. Simulated RF-DC conversion efficiency vs. frequency and load impedance of the proposed rectenna for an input power level of -10 dBm.

III. WIRELESS ENERGY HARVESTING AT THE UNIVERSITY OF LIVERPOOL

In addition to [18], [24], and [25], our most recent two contributions are: 1) A novel technique to maintain the high conversion efficiency of broadband rectennas in a varying load condition. 2) A novel technique to eliminate the need of a matching network in broadband rectenna designs. Both technologies were not reported in literature.

A. Hybrid Resistance Compression Technique

A resistance compression network (RCN) is a special network that can reduce the sensitivity and nonlinearity of electronic devices such as amplifiers, DC-DC converters and rectifiers [16]. Thus, the RCN could be employed in rectenna design to reduce the nonlinear effect when the loading condition is varying. However, since the performance of the RCN is heavily dependent on the operating frequency, the operational frequency bandwidth of the RCN is normally very narrow (e.g., FBW < 10%). Most reported designs are single band RCNs. Hence, the conventional RCNs are normally not suitable for broadband rectenna designs due to their limits of operating frequency. The RCNs have not been used in broadband rectenna designs in the literature.

Therefore, we propose a novel hybrid approach to apply the RCN in broadband rectenna designs. As shown in Fig. 1, a conventional broadband LC matching network is configured to match the impedance of the rectifier to 50 Ω over a frequency band from 450 (f_0) to 950 (f_1) MHz. Next, this network is transformed by reversing its input and output ports. The two networks were configured on two branches, as shown in Fig. 2(a). Two L-networks at the center frequency (f_c) of the band are added in both branches for improving the matching performance. The initial network (on the upper branch) shows a positive phase response (ϕ) of the input impedance over the covered frequency band (between f_0 and f_1), while the second network (on the lower branch) achieves opposite phase response (-ϕ) for the frequency band of interest. Thus, the proposed matching network may have resistance compression characteristics (opposite phase response of the input impedance) within the frequency band of interest, and have an enhanced impedance matching performance at the center frequency. The RCN is mixed with an impedance matching network to form a hybrid resistance compression technique (HRCT) [26]. The complete matching network is configured with a receiving antenna and two voltage doubler circuits, as shown in Fig. 2(b). The simulated RF-DC conversion efficiency of the proposed rectenna using this hybrid resistance compression technique (HRCT) is shown in Fig. 3. The input power level is -10 dBm. It can be seen that the efficiency is constantly high (e.g., > 40%) over a wide frequency band (from 0.5 to 0.9 GHz) and a load impedance range (from 5 kΩ to 60 kΩ). Therefore, it demonstrates that the proposed HRCT can reduce the nonlinear effects of broadband rectennas which is of highly significance for WEH used in real world applications. It is also shown that the RCN can indeed be used in broadband rectenna designs.

B. *Matching Network Elimination*

The aforementioned technologies have shown that, by improving the impedance matching network of a rectenna, the rectenna can be broadband or multiband and also of high conversion efficiency, while its performance can be maintained in different operating conditions. But, it is noted that the impedance matching networks for such broadband rectennas were relatively complex. More circuit components were added in the design which could increase the cost, loss, introduce errors in manufacture, and create additional problems.

From these facts, we propose a novel design of broadband or multiband rectennas. The aim is to eliminate the need for impedance matching networks and to improve the overall performance of the rectenna. As shown in Fig. 4, different from the conventional rectenna that uses 50 Ω ports for the antenna and rectifier, the proposed new antenna is a special high impedance antenna. The impedance of the antenna is of around 200 to 300 Ω for the real part and of around 0 to 300 Ω for the imaginary part in a wide frequency band. The value of the antenna impedance (X – jY) may directly conjugate match with the input impedance of a specific rectifier (X + jY) within the desired frequency range but mismatch at other frequencies (filtering response). Thus the matching networks can be eliminated and the proposed rectennas can offer high conversion efficiency in a broad bandwidth. Moreover, since both the rectifier and the antenna are of relatively high input impedance, the effects on the reflection coefficient (S_{11}) of the rectenna caused by the impedance variation of the nonlinear elements (rectifying diodes) may not be very significant. Therefore, compared with the conventional 50 Ω (low impedance) matching system, the non-linear effects of the rectenna can be significantly reduced by using this new configuration. The rectenna may have good performance in a range of operating conditions such as different input power levels, different load values, or even different types of rectifying diodes. In addition, the proposed rectenna configuration can reduce the total cost and avoid fabrication errors due to its very simple structure. As shown in Fig. 5, the rectenna has achieved high conversion efficiency in different operating conditions such as a wide frequency band, different input power levels, and also different types of rectifying diodes (results are cited from [27]). More detailed results will be presented at the conference.

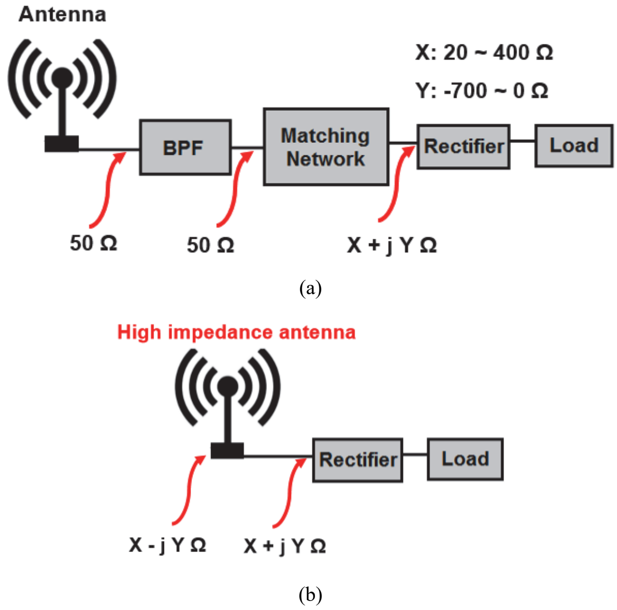

Fig. 4. Rectenna design (a) with and (b) without using an impedance matching network.

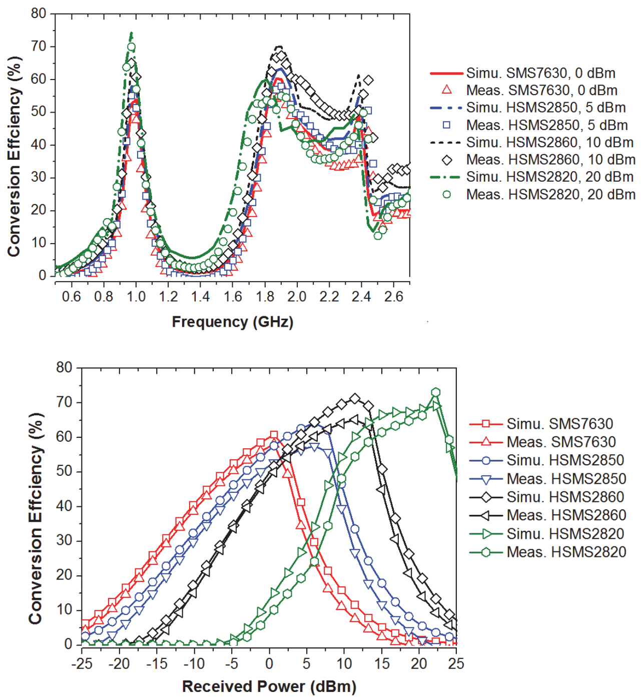

Fig. 5. RF-DC conversion efficiency vs. frequency and input power level of the rectenna. From [27].

IV. Conclusion

In this paper, we have reviewed the recent progress in the literature and presented some latest results from our group at the University of Liverpool, UK focusing on broadband and multiband rectennas for WEH and WPT applications. In addition to the existing technologies, we have developed a number of novel techniques, namely, a hybrid resistance compression technique and a matching network elimination technique to develop rectennas. These rectennas can achieve a very broad bandwidth, have a higher RF-DC conversion efficiency, and have consistent performance in a varying operating condition. The broadband rectenna without a matching network has the advantages of simple structure and low-cost. The state-of-the-art technologies presented in this paper could have a great impact on future development of rectennas and stimulate people's interest on their related applications.

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