FOCUSED ISSUE FEATURE

Optimum Behavior

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Today's society is evolving toward creating smart environments where a multitude of sensors and devices are interacting to deliver an abundance of useful information. Essential to the implementation of this Internet of things is the design of energy efficient systems aiming toward a low-carbon-emission society. Within this context, wireless power transfer appears as an alternative to providing these sensors and devices with self-sustained operation.

The concept of power transmission by electromagnetic waves initially appeared in the works of Hertz and Tesla [1]. The circuit that is used to convert electromagnetic power to dc power is the rectenna, which was patented by W.C. Brown in 1969 and consists of an active antenna combining a radiating element (antenna) with a rectifier circuit [2]. Initial applications of microwave

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power transmission focused on applications where directive, high-power transmission was required. Some of these applications focused on solar-power satellites where solar energy was captured and converted to electromagnetic signals that then could potentially be reradiated. Later on, the interest in autonomous sensors led to the concept of ambient electromagnetic energy harvesting or scavenging where rectennas are used to provide dc power by converting to dc available RF power from existing ambient low-power electromagnetic sources not specifically transmitting to power a sensor [3], [4].

Despite the existing works, there is still a lot of open issues when designing wireless-power transmission (WPT) systems, and a lot of challenges still to be achieved, especially on the receiving side. In order to obtain an optimum design of rectenna elements, it is necessary to accurately characterize and model the nonlinear rectifying element and also be able to perform a joint optimization of the antenna plus rectifier circuit to obtain the optimum performance. In this article, a general overview of WPT systems will be given followed by the explanation on how to model the behavior of Schottky diodes and how to use nonlinear optimization procedures in order to synthesize rectenna elements in an efficient manner. The issue of selecting the optimum signal waveform in the transmitting terminal for maximizing the RF-to-dc conversion efficiency of the receiving end as well as alternatives to provide autonomy to the transmitter will also be covered here.

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System Components

In general, wireless energy transfer can be seen as a contactless manner of transferring power to a system in order to power it. There are several classifications that can be made of wireless energy transfer systems attending to the transfer mechanism and the distance between the transmitting source and the device that needs to be powered. One of these classifications divides the wireless energy transfer mechanisms in near field and far field. Near-field mechanisms include inductive coupling and resonant inductive coupling. Far-field mechanisms include radiation of RF/microwave electromagnetic signals. This article presents a review of different concepts, models, and design techniques that can be used for far-field RF/microwave electromagnetic radiation WPT system design.

Figure 1 presents a simplified schematic of a WPT system based on electromagnetic radiation of RF/microwave signals. On one side of the system there is a transmitting terminal that radiates an RF signal at a certain frequency and with a certain power level. On the other side there is a rectenna element formed by an antenna and a rectifier circuit that collects the RF signal and converts it into dc power. One of the key parameters when designing WPT systems is the maximization of the RF-to-dc conversion efficiency of the rectenna element at the receiving end. Toward this goal, there are several issues that can be addressed both in the

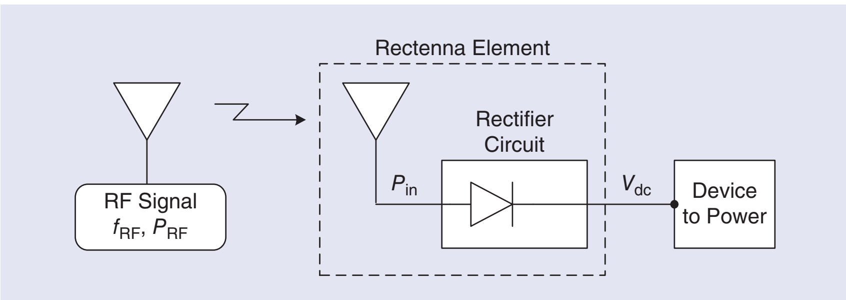

Figure 1. *A simplified schematic of a WPT system.*

transmitting and the receiving ends of the WPT system. This article covers these issues by focusing on one side on the design, modeling, and optimization of the receiving terminal of WPT systems in order to enhance its performance and on the other side on the selection of the optimum signal waveforms in the transmitting terminal aiming at maximizing the RF-to-dc conversion efficiency on the receiving end.

Nonlinear Analysis and Behavioral Model

As was already explained, an electromagnetic radiation WPT chain is essentially a system that converts dc energy in the transmitter to dc energy in the receiver with an RF air interface in the middle.

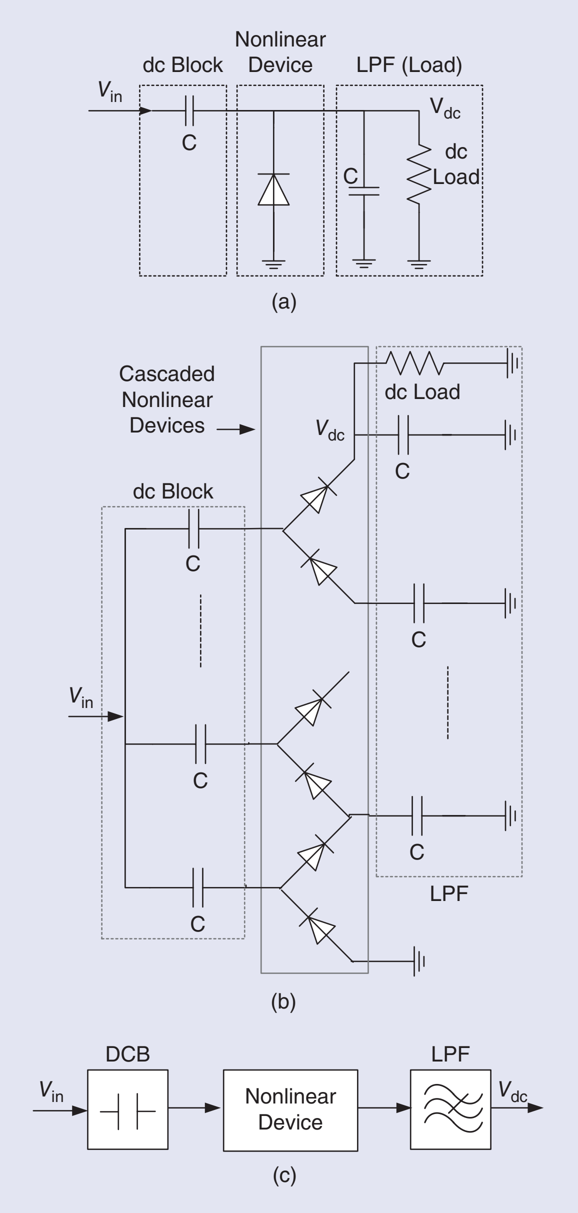

Figure 2. *RF-dc converters: (a) a single diode detector, (b) a charge pump Dickson configuration typically used in RFID tags, and (c) a block diagram of an RF-dc converter.*

The overall dc-dc efficiency can be improved by optimizing both the dc-RF and RF-dc circuits. However, since both of these circuits are strongly nonlinear, they should be optimized in a clever and enhanced way. The efficiency optimization in the transmitter part follows the same approach as in highly efficient power amplifiers used for wireless communications. Since this is a vast field of research, we will not focus on this discussion but rather on the nonlinear behavior of RF-dc converters based on diode bridges.

An RF-dc converter system is basically (the matching network circuits are not considered in this analysis) composed of an input dc block, a nonlinear device [Figure 2(a)] [or a cascade of nonlinear devices, as in a charge pump topology, Figure 2(b)], and an output low-pass filter (LPF).

When fed with an RF input signal, the nonlinear device produces several spectral components at the output: dc, fundamental frequency, harmonics of the fundamental, and intermodulation mixing products (if the input signal is modulated). Ideally, the low-pass output filter eliminates all the RF components, leaving only the dc component. Figure 2(a) depicts a single Schottky diode detector, which is commonly used in rectenna circuits. Figure 2(b) presents the typical configuration of a Dickson voltage multiplier, commonly used in passive ultrahigh-frequency (UHF) radio-frequency identification (RFID) tags. Finally, in Figure 2(c), one can see the block diagram of a general RF-dc converter. Conventional RF-dc converters can be represented as in Figure 2(c).

In order to understand the RF-dc conversion mechanism behind this class of converters, we will explain briefly the nonlinear behavior of an RF diode. An RF Schottky diode behavior is shown in Figure 3. The nonlinear relation between the total current flowing through a Schottky diode and its applied voltage is given by [5]:

$$I_D = I_S\left(e^{\frac{V_b}{nV_t}} - 1\right) = I_S\left(e^{\frac{V_{bext} - R_S I_D}{nV_t}} - 1\right), \qquad (1)$$

where I_s is the diode saturation current, V_b is the voltage across the Schottky barrier, n the diode ideality

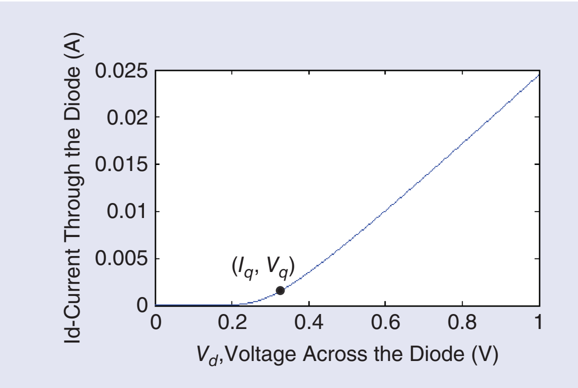

Figure 3. *A typical I–V characteristic of a Schottky diode.*

factor, V_t is the thermal voltage, and V_b is equal to an external voltage applied to the diode minus the voltage drop across the series resistance R_S.

At low bias levels, the voltage drop across R_S is insignificant, so the diode behavior is dominated by the Schottky barrier (small-signal quadratic region), while at higher bias levels the ohmic resistance R_S dominates (large-signal linear region) and the diode behavior is predominantly resistive.

The rectifying process in a Schottky diode barrier can be classified into two different types [6], [7]: small signal operation [Figure 4(a)] and large signal operation [Figure 4(b)]. The latter case concerns the rectification of a large input amplitude signal that forces the diode to operate in its resistive zone (where the diode behavior is dominated by the series resistance).

On the other hand, in the small-signal operation, the diode is driven by a very small signal amplitude. In this operation regime, the nonlinear relation can be written as a Taylor series expansion around a quiescent point. It should be noted that even though no dc quiescent point is externally applied, the rectifier will be dc-biased by a self-biasing mechanism: when fed with an RF signal, the diode generates a dc component that acts as a biasing point. In the small-signal regime, three different operating zones can be defined according to the bias level [Figure 4(a)]. In the first zone (Z1) or square law zone, the diode behavior is predominately quadratic so that the output signal is proportional to the square of the input signal and consequently proportional to the input power. This operating zone includes the zero-bias operation. As the bias level is increased, the diode enters the so-called transition zone (Z2), where other contributions start to have significant impact (Figure 4). The first two zones are considered in the next analysis. In the small signal regime, if the nonlinear device is biased in its resistive zone (Z3), then the output signal is proportional to the input signal. Therefore, in such conditions, no dc component is generated. This has no interest for RF-dc conversion.

Behavioral Model Used to Describe the RF–DC Converter

The previous presented diode (1) is a physical model based on physical parameters and so more difficult to deal with. Alternatively, in order to better understand the rectification process in a nonlinear device, (1) is approximated by a simple polynomial memoryless model:

$$y(t) = \sum_{n=0}^{N} k_n x(t)^n, \tag{2}$$

where $y(t)$ is the diode current and $x(t)$ is the voltage across the diode.

In order to simplify the explanation, the power series model is restricted to a simple polynomial series expansion around a quiescent operating point (X_q, Y_q). Hence, the model coefficients $k_1, k_2, \ldots, k_N$ can be directly obtained from the successive derivatives of the diode current [5] as in (3). The nonlinear mechanism and the impact of the biasing point are evaluated by extracting the first six order polynomial coefficients from the diode I–V curve of Figure 3. These coefficients are shown in Figure 5. For instance, if this particular diode was intended to be used for small signal power measurement, the best operation point would be in its square law region, where the second order coefficient k_2 is dominant. In this case, the output voltage would be approximately proportional to the square of the input amplitude voltage and so proportional to the input power

$$k_1 = \frac{1}{1!}\frac{\partial y(x)}{\partial x}\bigg|_{x=X_q}; \; k_2 = \frac{1}{2!}\frac{\partial^2 y(x)}{\partial x^2}\bigg|_{x=X_q};$$
$$k_n = \frac{1}{n!}\frac{\partial^n y(x)}{\partial x^n}\bigg|_{x=X_q}. \tag{3}$$

Despite this operational behavior, it should also be stressed that a correct match of the RF circuit should be gathered, since a maximum power transfer is fundamental to improve the RF-dc efficiency.

In order to achieve optimum input matching, the power-source impedance should equal the complex conjugate of the input impedance of the RF circuit. This type of matching is easily done in linear circuits,

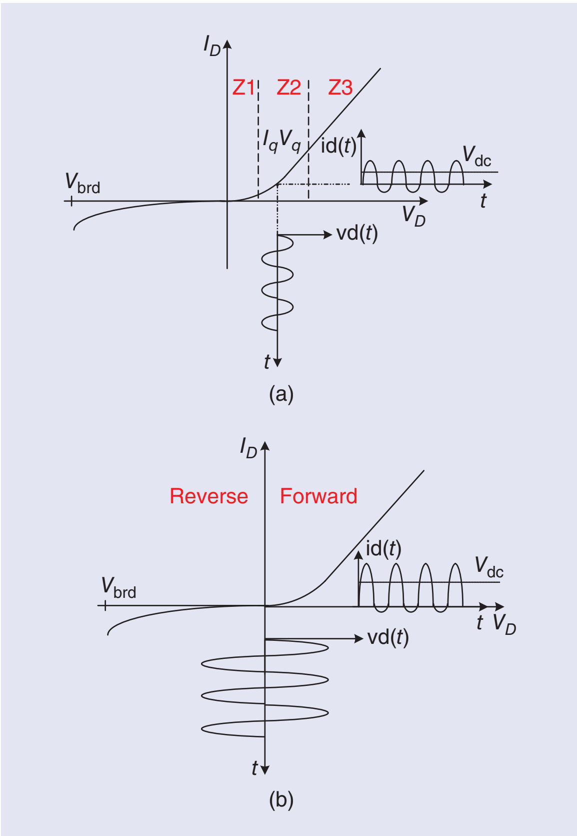

Figure 4. *The rectification process: (a) a small-signal operation and (b) a large-signal operation.*

where the input load of the circuit does not change with the input signal amplitude. However, since the input impedance of these nonlinear circuits significantly changes with the input signal level it is hard to get a conjugate impedance match for all values of input power. Typically, these circuits are designed for a specific value of input power level, preferably the operating input power level expected for the circuit. Improved designs also try to guarantee acceptable return loss for a wide range of input power levels. For this reason, a correct behavioral model that accounts for this change should be gathered in real circuits.

One of those behavioral model possibilities is the recently proposed polyharmonic distortion (PHD) model that somehow approximates the reactive behavior of the circuit, linearizing it in its large-signal operation. A good overview on the PHD model can be found in [8], and its application to RF-dc converters can be found in [9].

In this case, the input matching circuit should account for the PHD input large-signal scattering parameter and the conversion efficiency should account for the PHD transmission large-signal scattering parameter with a focus on the parameter relating input RF fundamental and the output dc.

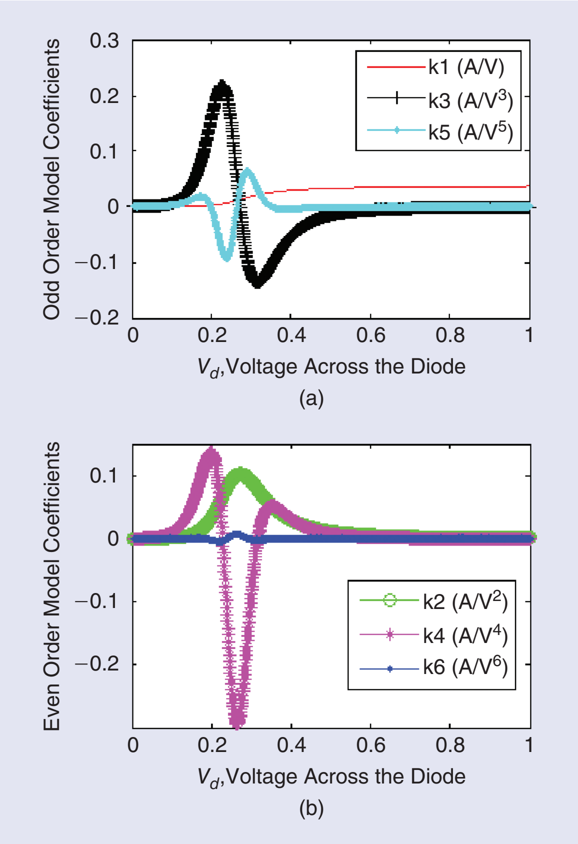

Figure 5. *Coefficients dependence on diode voltage V_d. (a) Odd-order coefficients, solid red: k1 (A/V), black: k3 (A/V^3), cyan: k5 (A/V^5). (b) Even-order coefficients, green: k2 (A/V^2), magenta: k4 (A/V^4), and blue: k6 (A/V^6).*

Optimized Design of Rectifier Circuits

As stated before, the element that is used to capture the electromagnetic signals and convert them into dc power is known as rectenna. A rectenna is formed by an antenna that collects the electromagnetic signals and a rectifier circuit that converts the incoming RF/microwave signals to dc power. Both the antenna and the rectifier circuit have to be appropriately designed in order to maximize the amount of dc power that can be obtained. The antenna must be designed to operate at the frequency at which the power has to be collected, and the rectifier circuit must be optimized to maximize its RF-to-dc conversion efficiency at this frequency.

The rectifier RF-to-dc conversion efficiency depends on the selected rectifying device, the rectifier topology, and the output load. Additionally, as mentioned in the previous section, it also depends on the available input power that reaches the rectifying element, so this parameter has to be taken into account when designing the rectifier circuit. The most commonly used rectifying devices are Schottky diodes or low or zero-barrier diodes when the amount of power that needs to be rectified is low [3]. There are also works that make use of pHEMT devices [10], as well as other MOS type devices connected in a diode topology in order to perform the rectification [11].

The typical topologies for rectifier circuits are the envelope detector where a single rectifying element is used and the charge-pump circuits where a ladder type structure with several rectifying devices is considered. Finally, both balanced and single-ended topologies resulting in full-wave and half-wave rectifiers, respectively, can be used, although commonly implemented rectifiers using off-the-shelf components tend to use half-wave rectifier circuits in order to minimize the number of components and simplify the circuit layout. Furthermore, in low-power scenarios minimizing the number of active devices usually results in a higher obtained efficiency (see "Optimal Rectifier Circuit Topology"). Regarding the rectifier output load, there is an optimum value for which a maximum RF-to-dc conversion efficiency can be obtained.

As previously explained, in order to maximize the RF-to-dc conversion efficiency of the rectifier

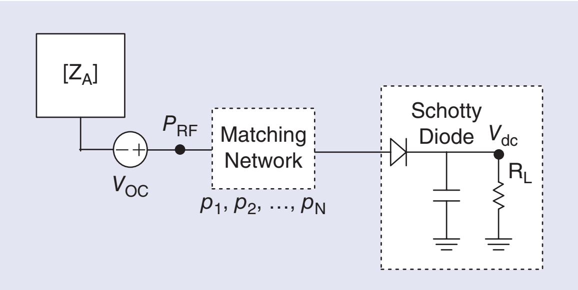

Figure 6. *A schematic representation of the optimization setup using the antenna Thevenin equivalent.*

Optimal Rectifier Circuit Topology

The RF-to-dc conversion efficiency depends on the topology selected for the rectifier circuit. However, depending on the amount of input power at the rectifier, topologies with less number of rectifying devices may lead to better RF-to-dc conversion efficiency. This is explained because of the need of a minimum amount of input power in order to switch the rectifying devices. Figure S1 shows that, for low-input power levels, topologies using a single-diode lead to better RF-to-dc conversion efficiencies than topologies with more diodes.

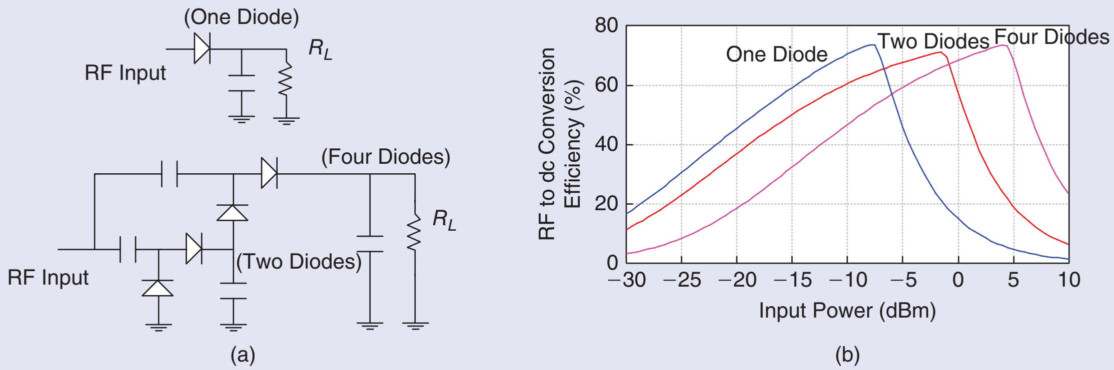

Figure S1. *RF-to-dc conversion efficiency dependence on the rectifier circuit topology. (a) Different rectifier topologies. (b) RF-to-dc conversion efficiency versus RF input power.*

circuit, it is important to introduce a matching net work between the antenna element and the rectifier circuit in order to maximize the power that reaches the rectifier. An optimum design of the matching network needs to consider jointly the antenna element and the rectifier circuit in the design stage. In order to be able to consider all these components simultaneously in the simulation stage, the Thevenin equivalent [12] (or Norton equivalent [13]) of the antenna in the receiving mode can be used (Figure 6). The Thevenin equivalent represents the antenna as an impedance matrix in series with an open circuit voltage source (V_{OC}). V_{OC} can be calculated using reciprocity theory [14] as follows:

$$V_{oc}(\theta_o,\phi_o,S)=\frac{4\pi}{jk\eta_o}F(\theta_o,\phi_o)E_o(S), \tag{4}$$

$$E_o(S)=\sqrt{2\eta_o S}, \tag{5}$$

$$\eta_o=120\pi, \tag{6}$$

where $F(\theta_0,\phi_0)$ is the electric far-field of the antenna in the transmit mode assuming unit current excitation, $E_o(S)$ is the electric field of an incoming plane wave referenced to the center of the antenna, S is the pointing vector of the plane wave, and η_0 is the free space impedance.

Harmonic balance simulation in combination with some optimization goals on the RF-to-dc conversion efficiency (7) can be used to obtain an optimum design for the rectenna element. A minimum value of desired RF-to-dc conversion efficiency at the desired frequency is imposed using optimization goals and the values of the matching network components as well as the rectifier load (R_L) are calculated to fulfill this goal

$$\eta=\frac{P_{\mathrm{DC}}}{P_{\mathrm{RF,av}}}=\frac{V_{\mathrm{DC}}^2}{P_{\mathrm{RF,av}}\cdot R_L}, \tag{7}$$

$$P_{\mathrm{RF,av}}=\frac{|V_{\mathrm{oc}}|^2}{8\cdot\mathrm{Re}(Z_A)}, \tag{8}$$

where $P_{RF,av}$ is the available RF power, and Z_A is the complex antenna impedance (Figure 6) and Re( ) indicates real part.

Using this optimization technique, it is possible to obtain single band, dual band, and broadband designs of rectifier circuits where the RF-to-dc conversion efficiency is optimized to be maximum at the

TABLE 1. Simulation set-up for RF-to-dc conversion efficiency in rectifier circuit.

Rectifier Type	Optimization Goals	Optimization Parameters
Single frequency f0	$\eta_{f0} > \eta_{\min}$	Matching network $[p_1, p_2, \ldots, p_N]$ R_L
Dual band f1, f2	$\eta_{f1} > \eta_{\min 1}$ $\eta_{f2} > \eta_{\min 2}$	
Broadband [fa-fb]	$\eta_{[fa-fb]} > \eta_{\min}$	

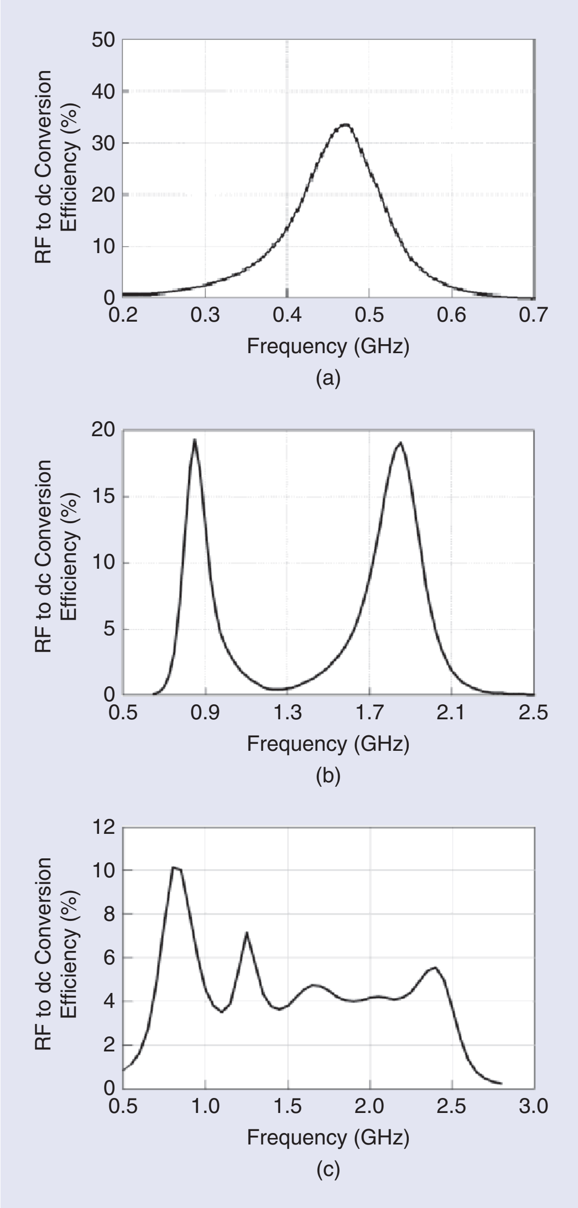

Figure 7. *Optimization results for three rectifier circuits using the harmonic balance simulations together with reciprocity theory: (a) single band, (b) dual band, and (c) broadband.*

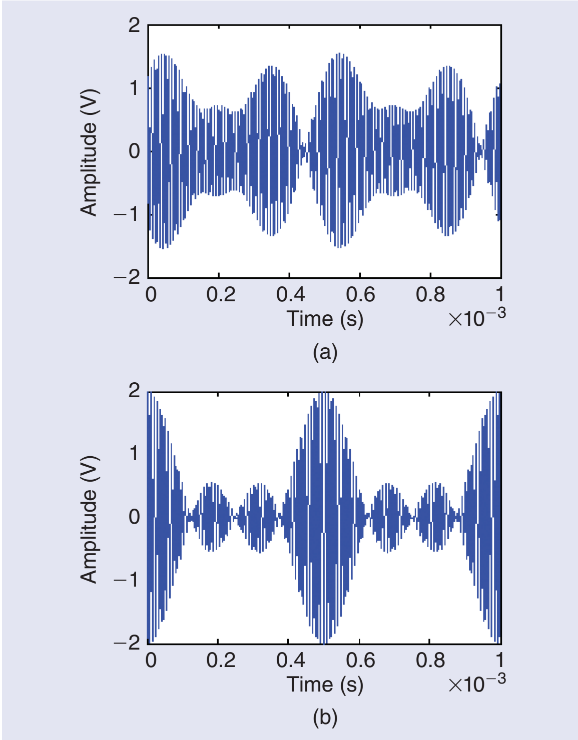

Figure 8. *Time-domain waveforms of multisine signals with different PAPR. (a) Random phase arrangement among the tones. (b) All tones in-phase (0°).*

selected frequency bands. Table 1 shows a summary of the design optimization set-ups that need to be used in the simulator for each of the different types of designs.

Figure 7 shows the performance results for three different types of rectifiers, all of them designed using the above procedure. The selected rectifier topology is a single diode envelope detector and the input power level is –20 dBm. Figure 7(a) shows the results of a single band rectifier circuit designed to have maximum RF-to-dc conversion efficiency at 450 MHz. Figure 7(b) shows a rectifier circuit designed to have a dual band performance at 0.85 GHz and 1.85 GHz. Figure 7(c) shows a broadband rectifier design. One important fact that can be seen from these designs is that as the number of frequencies at which the RF-to-dc conversion efficiency has to be optimized increases, the RF-to-dc conversion efficiency degrades. This is explained by the necessity of dual-band or broadband matching networks in multiband or broadband designs. These multiband and broadband networks usually have a reduced quality factor in comparison to single-frequency matching networks, which directly translates to a reduction in the transfer of power from the antenna terminal to the input of the rectifying element, which reduces the RF-to-dc conversion efficiency.

Table 2 presents a selection of state-of-the-art works for rectenna and rectifier circuit designs. Most of the rectifier designs in Table 2 are optimized for a single frequency of operation as this leads to higher RF-to-dc conversion efficiencies. In [3] and [18] designs for broadband rectifiers are presented that show that the RF-to-dc conversion efficiency is lower than in similar designs for single-frequency operation.

Optimal Signal Design for Maximum Efficiency in WPT Systems

The previous sections covered several issues that have to be considered and several actions that can be taken to improve the performance of a WPT system by focusing on the receiving end.

Another way of increasing the efficiency of RF-dc converters is by using special designed signal

TABLE 2. Comparison of state-of-the-art designs of rectifier circuits.

Reference	Frequency	Rectifier Topology	Pav (dBm)	Efficiency (%)	RL (Ohm)	V_{dc} (V)	Number of Elements	Polarization
[15]	450 MHZ	1 series diode	[−25… −7]	[0.05–45] at 450 MHz	5,600	[0.05–0.75]	No antenna	—
[3]	Broadband 2–18 GHz	1 shunt diode	[−17… +15] at 3 GHz	[0.1–20] at 3 GHz	100	[0.0025–0.79] at 3 GHz	64-element array	Left/right circular
[16]	10 GHz	1 shunt diode	[19–24]	[25–40] at 10 GHz	2,400	[6.92–15.5]	25-element array	Linear
[10]	900 MHz	E-phemt	[0–11.5]	[27–85] at 900 MHz	47	[0.11–0.75]	Single element	—
[17]	5.61 GHz	1 shunt diode	30	78	150	11	nine-element array	Circular
[18]	Broadband 0.8–2.5 GHz	1 series diode	−20	[4–8] at −20 dBm	3,100	[0.0352–0.0498]	Single element	Linear
[19]	Dual band 0.85/1.85	1 series diode	−20	[15/15] at −20 dBm	2,200	0.0574/ 0.0574	Single element	Linear
[18]	Dual band 0.85/2.45	1 series diode	−20	[18/10] at −20 dBm	2,200	0.0469/ 0.0629	Single element	Linear
[20]	24 GHz	1 shunt diode	27	43.6	40.2	2.96	12-element array	Linear

waveforms at the transmitting terminal that somehow will excite the diode nonlinear behavior in a more efficient way. Several works [21]–[23] have shown that this efficiency can be improved by selecting the most adequate input signal at the rectifier. Signals with large peak-to-average power ratios (PAPRs) provide higher RF-to-dc conversion efficiency than single-carrier signals, meaning that for the same targeted distance, one needs to transmit less power.

For instance, Figure 8 presents two different signals with the same average power but with different peak power. Figure 8(b) shows the time-domain waveform of a signal with a PAPR higher than the signal in Figure 8(a).

High PAPR signals can be obtained using multisine signals, where all the tones are in phase [22]–[23] or using signals that intrinsically present high PAPR, such as some type of modulated signals or chaotic signals [15].

In [22], the explanation on how to use this type of signal to increase the RF-dc efficiency can be seen in more detail, but it should be stressed here that

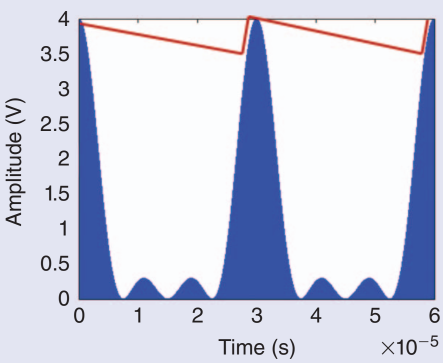

Figure 9. *Rectified waveform (with high peaks) and filtered waveform (with ripple) at the output of a rectifier excited with a high PAPR multisine signal.*

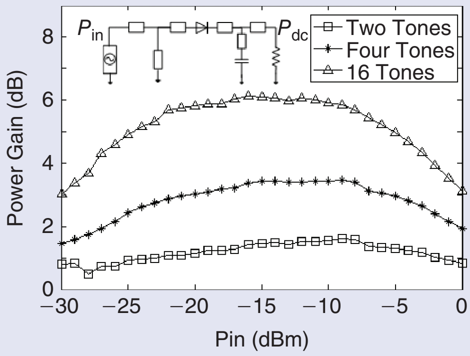

Figure 10. *Measured dc power gain (single diode detector) as function of input power, for different multisine signals.*

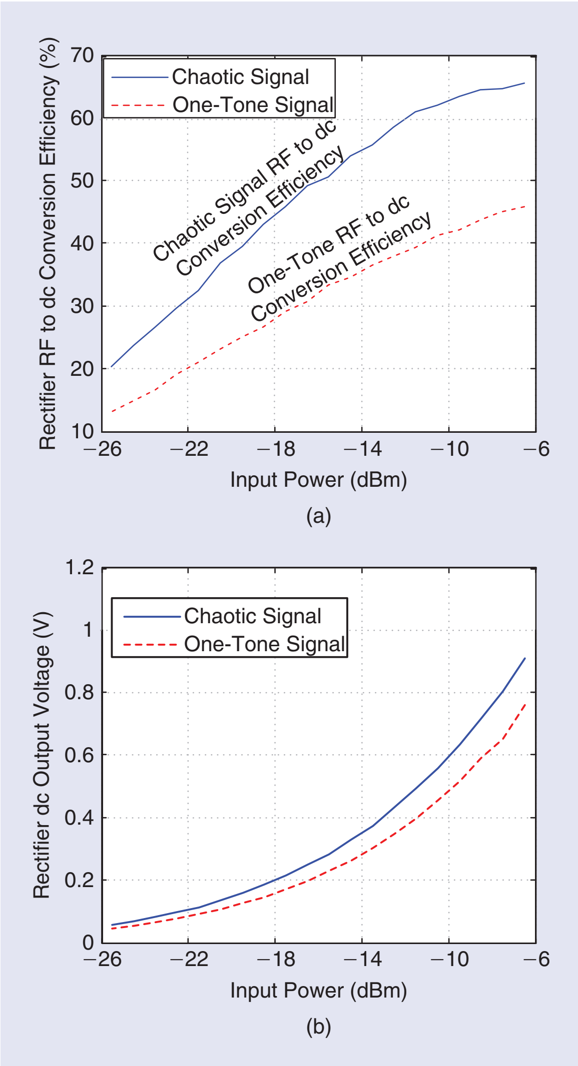

Figure 11. *Comparison of a rectifier circuit performance for one-tone and chaotic signals. (a) RF-to-dc conversion efficiency. (b) Output dc voltage.*

Figure 9 shows that a high peak means that the diode rectifier will increase the instantaneous voltage at a certain level, and if the low pass behavior of the output filter in the rectifier is well designed, the output capacitor will maintain this value stable until the next peak, so if we use a signal with the same amount of average power but with increased peaks, the energy conversion in the diode rectifier will be increased. A power gain figure G_p has been defined to evaluate the gain obtained with multisine signals. The gain G_p is defined as the ratio between the dc power obtained with a multisine signal and the dc power obtained with a single carrier with the same average power. Since in both cases the dc load resistance is the same, G_p can be defined as a function only of the dc voltages:

$$G_p = 10\log\left(\frac{P_{DCNTone}}{P_{DC1Tone}}\right) = 10\log\left(\frac{V^2_{DCNTone}}{V^2_{DC1Tone}}\right). \quad (9)$$

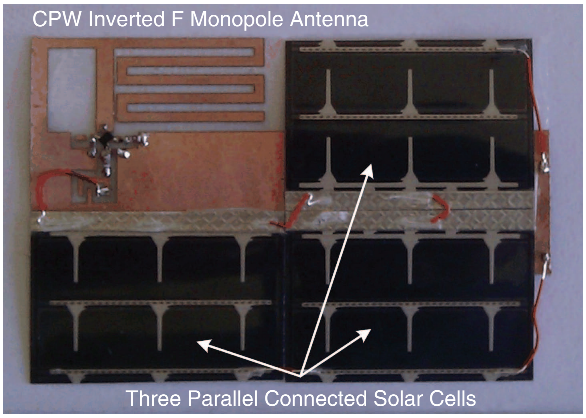

Figure 12. *Solar powered RF signal generator.*

Figure 10 shows the obtained increase in RF-dc conversion when using different kind of in phase multisine signals applied to a single diode rectifier. The improvement that can be obtained in the RF-to-dc conversion efficiency when using high PAPR signals is limited by the diode performance. If the overall PAPR increases significantly, the diode circuit starts working in compression and both the output signal and the RF-to-dc conversion efficiency stop improving.

In the same manner, as in phase multisine signals, chaotic signals intrinsically present a high PAPR, so potentially they can also be used to improve the performance of rectifier circuits in terms of RF-to-dc conversion efficiency.

Figure 11 shows some results obtained from measuring the performance of a single band rectifier at 450 MHz, when using a single tone RF signal at its input and when using a chaotic signal with equivalent total power but higher PAPR. From Figure 11 it can be seen that the performance of the rectifier circuit in terms of RF-to-dc conversion efficiency is improved around 10% for input power levels of −20 dBm and 20% for input power levels of −6 dBm.

Solar to EM Wireless Power Transmission

Further improvements can be sought on the transmitting terminal of a WPT system by exploiting ambient energy sources such as solar to be used in the generation of the electromagnetic signals in the WPT system. This idea was initially conceived for its use in solar-power satellites [24], where satellite units collect solar energy and use it to generate electromagnetic signals that can be sent toward earth in order to obtain dc power from them.

On a smaller scale, the use of solar-based electromagnetic signal generation for ground applications has also been explored. Low-consumption active antenna oscillators that are powered by means of solar cells have been demonstrated in [25]. Solar energy is captured using solar cells, then converted to dc and used to bias a highly efficient oscillator element that transmits its output signal through the antenna element.

In order to take further advantage of the area that the transmitting antenna elements occupy, the solar cells can share the same area with the antenna elements. This way, a compact structure that is capable of harvesting solar energy and, at the same time, transmit electromagnetic signals for WPT can be obtained. The location of the solar cells is selected in order to minimize the effect that they have over the antenna performance [25], [26].

Figure 12 shows a credit-card size prototype of a solar to electromagnetic signal generator. The antenna element is a meander-type antenna, and it is part of an active antenna oscillator operating at 900 MHz. Three solar cells connected in parallel are placed on the ground plane of the antenna to provide the necessary biasing for the oscillator to operate. By connecting the solar cells in parallel, the total current is multiplied by three while the voltage remains the same. The used solar cells are flexible amorphous silicon (a-Si) solar cells. Each of the unit cells in Figure 12 can provide up to 0.9 V and 20 mA. The complete solar cell structure, formed by the three unit cells connected in parallel can provide 0.9 V and 60 mA. Such circuits can be used to create autonomous RF signal generators that can be used as the RF-power terminals in a WPT system.

Conclusion

In this article, the different challenges and open issues regarding WPT systems have been presented considering both the transmitting and receiving ends. The challenges in the receiving side include the accurate modeling of the rectifying elements, the adequate selection of the rectifier topology, and the joint optimization of antenna and rectifier circuit. The challenges in the transmitting side are mainly in the improvement of the dc-to-RF conversion efficiency and in the selection of the optimum transmitted signal waveform. The final goal of most of these challenges is to take advantage of the nonlinear nature of the rectifying elements in order to maximize the RF-to-dc conversion efficiency in the receiving end of WPT systems.

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