INVITED PAPER

Array Designs for Long-Distance Wireless Power Transmission: State-of-the-Art and Innovative Solutions

A review of long-range WPT array techniques is provided with recent advances and future trends. Design techniques for transmitting antennas are developed for optimized array architectures, and synthesis issues of rectenna arrays are detailed with examples and discussions.

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ABSTRACT | The concept of long-range wireless power transmission (WPT) has been formulated shortly after the invention of high power microwave amplifiers. The promise of WPT, energy transfer over large distances without the need to deploy a wired electrical network, led to the development of landmark successful experiments, and provided the incentive for further research to increase the performances, efficiency, and robustness of these technological solutions. In this framework, the key-role and challenges in designing transmitting and receiving antenna arrays able to guarantee high-efficiency power transfer and cost-effective deployment for the WPT system has been soon acknowledged. Nevertheless, owing to its intrinsic complexity, the design of WPT arrays is still an open research field whose importance is growing as the possibility to transfer energy by means of electromagnetic waves gathers more and more interest from the applicative viewpoint. This paper is aimed at reviewing the array design approaches proposed in the state of the art for long-range wireless power transmission, highlighting the latest advances and innovative solutions as well as envisaging possible future trends of the research in this area.

KEYWORDS | Array antennas; solar power satellites; wireless power transmission (WPT)

I. INTRODUCTION

Long-range wireless power transmission (WPT) systems working in the radio-frequency (RF) range [1]–[5] are currently gathering a considerable interest (Fig. 1) for their envisaged applications in those scenarios where the deployment of electrical wired networks is unfeasible or cost ineffective [6]–[13]. Indeed, RF-based WPT is a promising technique for supplying not-accessible fixed and mobile systems and, unlike other wireless power transfer technologies exploiting near-field coupling (which guarantee efficiency up to 70% but operate over distances of the order of the wavelength [14]), or laser beaming (which still present several technological challenges [15]), to transfer power over large distances by exploiting well-assessed technologies [4]–[6], [8], [9]. Enabled applications include powering distributed electronic devices such as mobile phones and laptops [16], [17], feeding pervasive sensors and actuators (e.g., wireless sensor nodes and robots) [18], transmitting energy in inaccessible or

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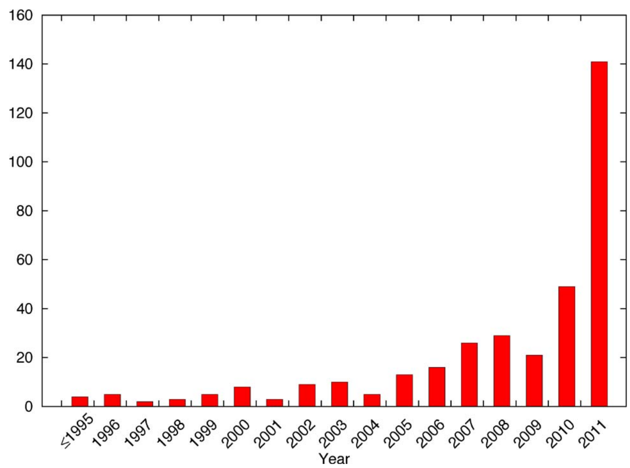


Fig. 1. ***The number of WPT-related papers published each year (based on IEEE Xplore databases).***

hazardous regions to enable sustainable existence, and "fueling" electrical vehicles [19], [20], unmanned aerial vehicles (UAVs), and high altitude platforms (HAPs) [9], [21]. Moreover, WPT is one of the proposed technologies for the space-to-earth transfer of electrical energy gathered by "solar power satellites" (SPSs) [1], [3], [5], [6], [8], [22]–[25].

Generally speaking, WPT systems operating over long distances require the transmission of RF electromagnetic beams from the generating point to (at least) one faraway receiver, which is responsible for the collection and RF-to-DC conversion of the impinging waves [1], [3], [5], [8]. Consequently, the fundamentals of WPT technologies are not completely new, as they are loosely related to those of wireless communications and radar systems [5], [8], [10]. However, owing to the specific objectives of WPT applications (i.e., transmission of power instead of information), the long-term viability of such systems requires to address their constraints and goals through a new perspective in terms of theoretical tools and design approaches [10].

The above considerations are specifically true for the two key components that enable the electromagnetic power transfer [3], [8], [23], [26], namely the *transmitting* [2], [27]–[30] and *receiving* antenna arrays [32]–[34]. Indeed, owing to the requirement of maximize the end-to-end power efficiency of WPT systems (i.e., the ratio between the output power at the receiving antenna and the input power at the transmitting antenna), "unusual" constraints arise for the array design problems [8], [28]–[30], [32]–[34]. More specifically, while the transmitting array must coherently focus the *transmitted power* in a narrow angular sector corresponding to the receiver aperture (possibly minimizing the sidelobes) [2], [28]–[30], the receiving array has to maximize the ratio between incident and collected RF power [31]–[34]. The development of techniques suitable for the above problems turns out to be even more challenging because simple, light, reliable, compact, and robust architectures are required for WPT applications [8], [28]–[30], [32]–[34].

Such objectives, which are generally neglected or only partially addressed by traditional antenna systems (mainly devoted to optimally transfer information) [8], are forcing the array community to face so many new challenges to require significant theoretical and practical developments [8], [28]–[30], [32]–[34].

Accordingly, the aim of this paper is to survey the present state of array design theory and techniques for long-distance WPT, to give a comprehensive report on the latest progress in the field, and to review the envisaged future trends of the research in this context. Toward this end, the reference WPT array synthesis problems are briefly recalled in Section II both for the transmitting (Section II-B) and receiving (Section II-C) layouts. Afterwards, the state-of-the-art WPT array design techniques for the radiating (Section III) and collecting (Section IV) architectures are reviewed also discussing a set of recent experiments and prototypes concerning innovative long-distance WPT systems. Finally, some conclusions are drawn (Section V).

II. WPT DESIGN PROBLEMS

A. End-to-End RF System Efficiency

Fig. 2(a) is a high-level illustration of the architecture of the reference long-distance WPT system [1], [3], [5], [8]. In such a scenario, a transmitting array is fed by a DC source with power $P_{\rm IN}$ (e.g., the electrical network in a earth-to-earth application, or a set of orbiting solar panels in the SPS case). The feeding network is responsible for the DC-to-RF conversion and of the powering of radiating elements (examples include dipoles [1], waveguide slots [35], horns [23], [36], and microstrip patches [26], [37]). Each antenna of the array coherently transmits a wave with a desired amplitude and phase [Fig. 2(b)], so that the overall beam is suitably shaped toward the collecting area [23], [28]–[30]. From the receiving array side, the antennas are responsible to gather the impinging RF wave and to convert it to DC power [Fig. 2(c)] [8], [32]–[34]. Toward this end, a rectifying circuit is integrated in each element (or subset of them), which is consequently named *rectenna* [Fig. 2(c)] [31], [33], [34]. The overall converted power $P_{\rm OUT}$ is then summed at the DC level and then sent toward the load [Fig. 2(a)].

According to the above description and to the schematic diagram in Fig. 3, the end-to-end RF efficiency, defined as [8]

$$E_{\rm RF} \triangleq \frac{P_{\rm OUT}}{P_{\rm IN}}$$

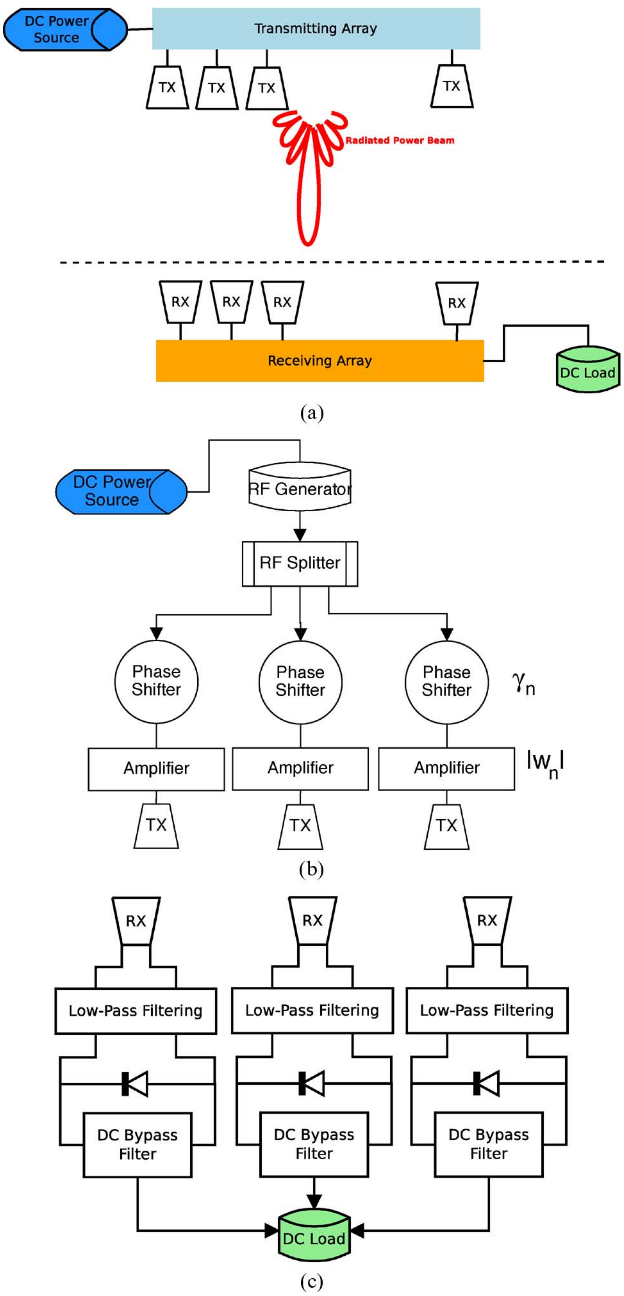


Fig. 2. ***Typical structure of a long-range WPT system (a). Schematic of (b) transmitting and (c) receiving WPT arrays.***

can be simply computed as

$$E_{RF} = \frac{P_{RX} \times E_5}{P_{IN}} = \frac{P_{INC} \times \prod_{j=4}^{5} E_j}{P_{IN}} = \frac{P_{RAD} \times \prod_{j=3}^{5} E_j}{P_{IN}} = \frac{P_{TX} \times \prod_{j=2}^{5} E_j}{P_{IN}} = \frac{P_{IN} \times \prod_{j=1}^{5} E_j}{P_{IN}} = \prod_{j=1}^{5} E_j \quad (1)$$

where $E_1 \triangleq P_{TX}/P_{IN}$, $E_2 \triangleq P_{RAD}/P_{TX}$, $E_3 \triangleq P_{INC}/P_{RAD}$, $E_4 \triangleq P_{RX}/P_{RAD}$, and $E_5 \triangleq P_{OUT}/P_{RX}$ are the subsystem efficiencies (Fig. 3). Consequently, the end-to-end efficiency E_{RF} of a long-range WPT system is mainly related to:

1) the efficiency of the DC-to-RF conversion in transmission and radiation (i.e., $E_1 \times E_2$);
2) the capability to suitably shape the radiated beam toward the collecting area (i.e., E_3);
3) the capability to gather the incident power at the receiver (i.e., E_4);
4) the efficiency in the RF-to-DC conversion in reception (i.e., E_5).

Owing to the focus of this overview, attention will be paid in the following to the key points 2 (Section II-B) and 3 (Section II-C). The reader is referred to [38] and [39] for a more detailed discussion on 1 and 4.

B. Transmitting Array

As stated above, the fundamental requirement for the transmitting array in a WPT system is its ability to maximize E_3 by radiating the RF power toward the collecting region through a suitable (real time, when mobile applications are of interest) beam control strategy [2], [8], [23], [28]–[30]. Accordingly, WPT transmitting arrays must be able to:

a) steer the beam toward the receiver direction (with respect to the transmitter) [Fig. 2(a)];
b) shape the radiated beam through suitable weighting strategies so that the power sent toward the receiver aperture Ω [i.e., the collecting area (in sterad) occupied by the receiver] is maximized.

1) Real-Time Steering Problem: With regard to a), retrodirective beam control systems have recently emerged as the most reliable techniques to guarantee an accurate beam steering in WPT applications [8], [17], [22], [40], [41]. Such systems are based on the emission of a *coded* pilot signal from the receiver toward the transmitting array, which is used as a reference to steer the beam backwards [23], [40], [41]. In such a framework, the steering problem can be formulated as follows [23], [41].

> *WPT Array Steering Problem*: Given the (complex) voltages r_n, $n = 0, \ldots, N-1$, collected by a set of N array elements located at (x_n, y_n), $n = 0, \ldots, N-1$, when illuminated by the *pilot signal*, compute the phases γ_n, $n = 0, \ldots, N-1$, to be used to feed each transmitting antenna so that the radiated beam is focused toward the receiver.

Such a problem can be classified as a direction-of-arrival (DoA) estimation with pilot signal [42]. Thanks to the cooperative nature of the receiver, the WPT array steering problem can be effectively solved through a phase conjugation scheme [40] according to the following steps [8], [41]:

1) capture the phase of the pilot signal ($\chi_n \triangleq \angle r_n$);

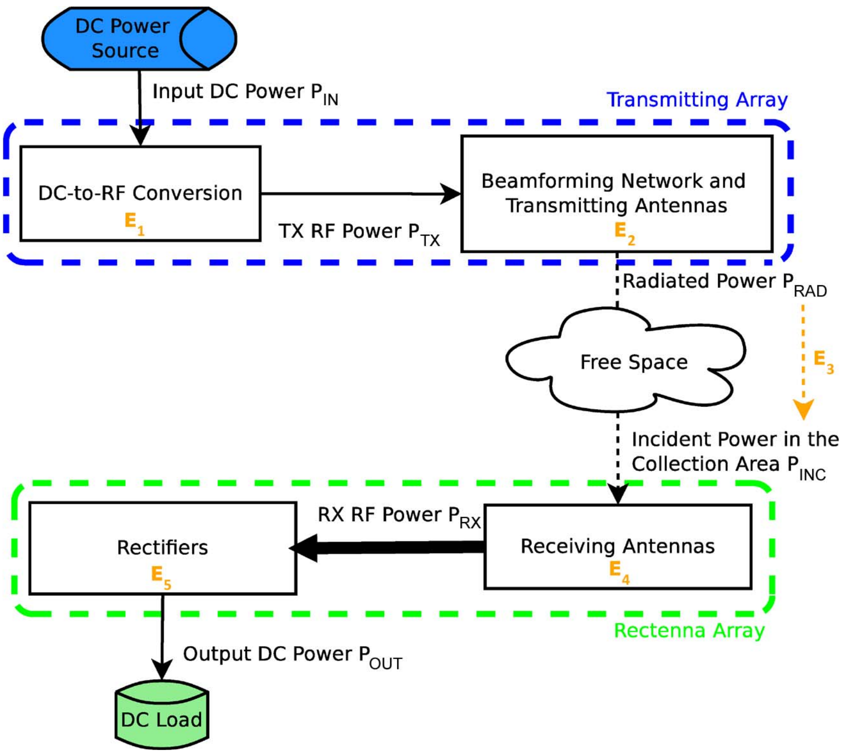


Fig. 3. ***Schematic diagram of the main blocks of a long-range WPT system.***

2) for each element, compare χ_n with the onboard reference phase $\widehat{\chi}$ (distributed throughout the array by means of a local oscillator), and compute the phase difference $\Delta\chi_n \stackrel{\Delta}{=} \chi_n - \widehat{\chi}$;
3) feed the nth element with the phase $\gamma_n = -\Delta\chi_n$ (*conjugation*) so that the arising wavefront is collimated toward the receiver.

Beyond its simplicity (see [22] and [40] for some experimental realizations), retrodirective steering has the advantage of enabling automatic safety procedures in the absence of a pilot signal (through beam spreading caused by dephasing) [8]. Owing to these features, such a methodology is at present the reference one for the solution of the WPT array steering problem, although other techniques have been proposed as well (see Section III-E).

2) Beam Shaping Problem: A more challenging problem arises concerning the issue b). Indeed, the WPT beam shaping problem is usually formulated as a *power-efficiency* maximization one, but taking also into account application-specific constraints (e.g., in terms of complexity, robustness, or achieved sidelobe level) [8], [28]–[30], [43], [44].

More in detail, the goal of the beamforming procedure is to define the "simplest" weights w_n, $n = 1, \ldots, N$, to be used to feed each radiating element [located at (x_n, y_n), $n = 0, \ldots, N-1$] so that the arising E_3 (also called beam collection efficiency) is maximized. From the mathematical viewpoint, and with reference to the model of the WPT system depicted in Fig. 2(a), E_3 can be computed by noticing that P_{RAD} and P_{INC} are equal to, respectively

$$P_{\mathrm{RAD}} = \int\limits_{(u^2+v^2)\le 1} |W(u,v)|^2\, du\, dv$$

$$P_{\mathrm{INC}} = \int\limits_{\Omega} |W(u,v)|^2\, du\, dv$$

where $W(u,v) = \sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)}$ is the synthesized beam,[1] $k = 2\pi/\lambda$ is the wave number $u = \sin(\theta)\cos(\varphi)$ and $v = \sin(\theta)\sin(\varphi)$ (the usual spherical coordinate system has been assumed) [45]. Accordingly, the general beam shaping problem can be formulated as follows [30], [43], [44].

WPT Beam Shaping Problem: Given a set of N radiating elements located at (x_n, y_n), $n = 0, \ldots, N-1$, find the array weights w_n, $n = 0, \ldots, N-1$, such that $E_3 = \int_\Omega \left|\sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)}\right|^2 du\, dv / \int_{(u^2+v^2)\le 1} \left|\sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)}\right|^2 du\, dv$ is maximized with the simplest, lightest, most reliable, most compact, and most robust feeding network.

[1]The $W(u,v)$ expression could be modified to include element coupling effects [45]. However, in the following, such effects will be neglected for simplicity: the reader is referred to [46] for an exhaustive discussion on such a topic.

Given the tradeoff performance complexity of the synthesis problem, no unique solution exists, since all the above target parameters cannot be jointly realized in practice. On the other hand, most applications need a few target parameters to be optimized. Accordingly, several different weighting strategies have been proposed whose effectiveness depends on the size, target efficiency, and costs for the specific application (see Section III).

C. Receiving Array

With reference to the WPT scenario in Fig. 2(a), let us assume that M receiving elements displaced in (x_m, y_m) $(m = 1, \ldots, M)$ are responsible for the collection of the incident electromagnetic power [47].

In this framework, the most widely adopted strategy consists in the use of a noncoherent reception scheme in which each element is responsible for the reception and RF-to-DC conversion of the incident power, which is then combined in a common DC bus [Fig. 2(c)] [4], [47]. Such a solution, which is unique to WPT systems, is usually preferred over a standard "phased array" configuration because of its desirable characteristics, which include i) its architectural simplicity, which avoids expensive, heavy, and complex RF network in reception [31], [33], [48]; ii) its intrinsic redundancy [47]; and iii) its modularity and stability with respect to frequency, level of input power, and interferences [4], [48].

However, this choice yields to a completely different design problem with respect to those of classical phased array antennas [31]–[34]. Indeed, if a noncoherent reception scheme is adopted [Fig. 2(c)], then:

- weighting and phasing of the incoming waves is useless (as they are converted to DC before the combination) [33]; accordingly (unlike classical phased arrays), the only DoF in the design procedure is represented by the choice of element shape/size and position (x_m, y_m) [31], [47], [49];
- because of the nonlinear nature of the rectifying components (e.g., diodes), the analysis of the rectenna performances requires the exploitation of nonlinear or linearized circuit models [50], which must suitably take into account also the DC combination scheme (e.g., series, parallel, or cascaded interconnections) [31], [33].

According to the above considerations, the overall WPT rectenna array design problem turns out to be significantly different from classical phased array problems [49]. Consequently, the following reference WPT reception problem will be considered hereinafter:

> *WPT Receiving Array Problem*: Given a set of M antenna elements, find their location (x_m, y_m), $m = 0, \ldots, M-1$, and the associated RF-to-DC conversion network architecture such that E_4 is maximized with the simplest, lightest, most reliable, most compact, and most robust architecture.

Analogously to the WPT beam shaping problem, an optimal tradeoff satisfying the *performance* and *simplicity* requirements is prevented. Consequently, various techniques will be reviewed in the following, aimed at achieving solutions characterized by different complexity, achievable efficiency, and costs (see Section IV).

III. DESIGN TECHNIQUES FOR TRANSMITTING ANTENNAS

The WPT beam shaping problem has initially received less attention than the design and arrangement of rectenna system to be used in long-distance WPT [51], although its importance on the efficiency of wireless power transmission systems had been noticed early [52], [53]. More recently, a large number of methodologies have been proposed to obtain tradeoff solutions in terms of feeding network complexity, achievable performances, and design simplicity [27].

A. Uniform Weighting and Spacing

The simplest approach which has been considered consists in the exploitation of *uniform arrays*, that is, of regular layouts with uniformly excited elements, which is (assuming a normalized amplitude) [26], [35], [42], [54]

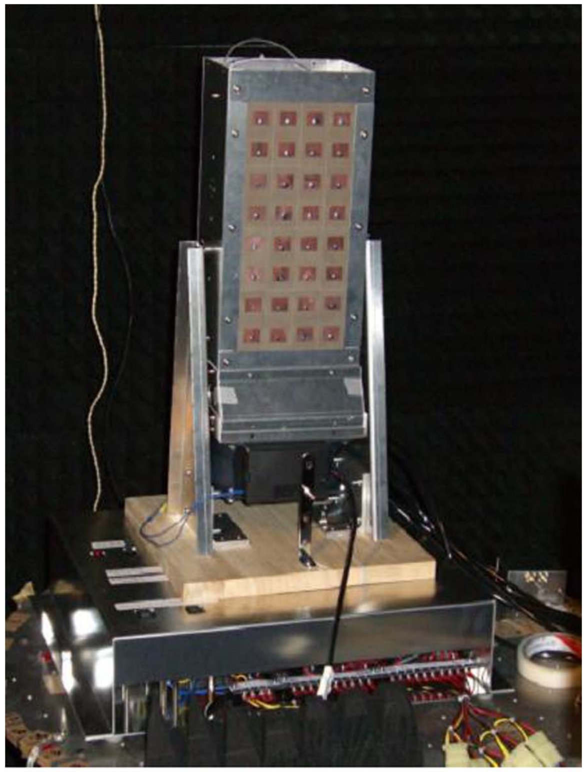
$$|w_n| = 1. \tag{2}$$

Such a choice is motivated by practical considerations of fundamental importance for WPT [26], [35]. More specifically, by using transmitting modules with fixed and equal gain, the fabrication, maintenance, and substitution of the feeding network components is greatly simplified [26], [35]. Moreover, the calibration of such system is eased up as well, since their only DoF is the phase shifting applied to each element [26], [35]. Both features represent key factors especially in those applications where the complexity of the array architecture and of its maintenance procedures must be as low as possible, even at the expenses of a suboptimal transmission efficiency (e.g., space-to-earth scenarios) [8], [26].

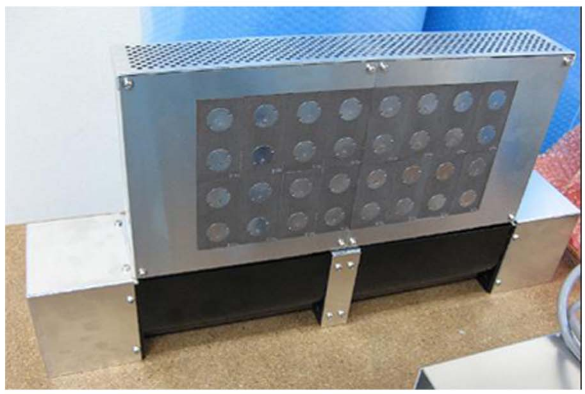
As a practical example of such methodology, in [26], a 5.8-GHz transmitting phased array with 256 elements conveying an overall 1.5 kW of power has been realized by displacing the radiating antennas on a triangular lattice and feeding each one (i.e., a circularly polarized microstrip patch) with a high-power amplifier (providing 6 W in output) and a 5-b digital phase shifter. Such a prototype has been able to achieve a remarkable beam steering accuracy (error below 0.1°) despite its minimal complexity in terms of array design [26]. A similar concept has been also considered for the development of an active integrated antenna (AIA) for long-range WPT, which has been based on the combination of a waveguide power divider and a slot-coupling feeding network (integrating a power amplifier and a phase shifter) to achieve independent phase shifting at 5.8 GHz for each radiating element [35].

In the same line of reasoning, but with the aim of further reducing the architecture complexity, the exploitation of subarrayed schemes has been proposed as well [40]. In such structures, the simplification is enabled by the fact that a single transmitting module (comprising a power amplifier and a phase shifter) is used to feed a set of radiating elements. For instance, a small-scale WPT antenna has been designed by combining two subarrays, each one comprising 63 circularly polarized truncated microstrip patch antennas ($w_n = \exp(\gamma_1), n = 0, \ldots, 63$; $w_n = \exp(\gamma_2), n = 64, \ldots, 127$) [40]. Owing to the considered architecture, the array has been able to effectively deliver and steer a 40-W beam at 5.8 GHz by using only two power amplifiers and two phase shifters [40]. However, the drawback of such solutions is the reduced field of view for the system (i.e., a maximum steering angle of $\pm 5^\circ$ has only been achieved in [40]).

Most current WPT demonstrators are based on uniform feeding strategies for the transmitting array [36], [55]–[57]. As an example, equally weighted radiating modules have been used in the experimental validations presented in [56] and [57] to deploy a large radiating structure able to transmit 20 W at about 150 km at competitive costs. Similar considerations apply also to smaller layouts [36], [58]. For instance, in [36], a set of five equally weighted horn antennas working at 5.8 GHz have been employed to supply a microaerial vehicle with a 4-W beam. Thanks to such a choice, a compact and efficient feeding network comprising modular amplifiers and phase shifters has been developed [36]. Moreover, a rover-feeding WPT transmitting system based on 4×8 uniform planar arrangements has been demonstrated in [58] (Fig. 4). In such a case, a further reduction of the array complexity and costs has been obtained either by realizing a (fixed) broadside-steering feeding network [Fig. 4(a)], or by integrating the entire structure in a single high-efficiency module [Fig. 4(b)] [58].



(a)



(b)

Fig. 4. ***Prototypes of transmitting systems for WPT-fed rovers [58]. (a) The 4 $\times$ 8 element AIA with no steering capabilities. (b) The 4 $\times$ 8 active integrated phased-array antenna (AIPAA).***

B. Closed-Form Design Techniques

An improved end-to-end efficiency can be achieved by nonuniformly weighting the antenna elements [28]. In this framework, the simplest approaches have been based on simple tapering windows to design the feeding network [28], [29], [59], [60].

As an example, the use of a Gaussian taper has been proposed in [60] to achieve improved transmission efficiencies (E_3) in long-distance WPT arrays [27]. More specifically, the following tapering window has been investigated in [27], [60]:

$$|w_n| = \exp\left[\frac{\ln(A_0)\left(x_n^2 + y_n^2\right)}{R^2}\right] \tag{3}$$

where R is the transmitting aperture size (in wavelength), and $A_0 \geq 0$ is a user-defined parameter controlling the tapering level. Such a choice, which is motivated by the fact that continuous Gaussian apertures are known to yield efficiencies close to the optimal ones [61] (e.g., $E_3^{\text{opt}} \approx$ 99.53% versus $E_3^{\text{Gauss}} \approx$ 99.31% when apertures with Fresnel number equal to 5.0 are at hand [62, Table I]), and that the arising windows can be computed easily [see (3)] whatever the aperture size, has been shown to yield good performances if compared with equally tapered layouts (e.g., $E_3^{\text{UNI}} \approx$ 83.8% versus $E_3^{\text{Gauss}} \approx$ 99.7%

assuming that Ω coincides with the transmitter mainbeam [27]).

Unfortunately, owing to its "smooth" nature, Gaussian taper has the main drawback of resulting in an architecture comprising a different amplification for each array element, thus turning out complex to be realized and maintained [28], [59]. To simplify such a structure, alternative approaches have been proposed which are based on the concept of *edge tapering* [28], [59]. In such techniques, the innermost elements of the array are fed with a constant amplitude, and only a small number of antennas close to the aperture border need different amplifiers [28], [59]. More specifically, the isosceles-trapezoidal distribution (ITD) has been introduced in [28] by defining in the linear case [i.e., $(x_n, y_n) = (nd, 0)$] the (normalized) tapering shown in (4) at the bottom of the page, where d is the lattice spacing, $\alpha_0 \in [0, 0.5]$ is (user-defined) size of tapering region, and $A_0 \geq 0$ is the tapering level [28], [59]. By analyzing the performances of several different ITD layouts and comparing them with Gaussian and uniform arrangements, it has been shown in [28] that the former often yield a performance improvement in term of total transmission efficiency. For instance, it has been shown that a 25 $\times$ 25 ITD arrangement ($d = 0.75\lambda$, $\alpha_0 = 0.25$, $A_0 = -18$ dB) working at 5.8 GHz achieves an efficiency which is almost 3% above the corresponding Gaussian layout ($A_0 = -18$ dB) and more than 10% above a uniform array of the same size (a 9.4 $\times$ 10-m^2 side square receiving aperture at 1 km has been assumed) [28]. Such results, together with the fact that (4) is easily computable whatever the array size and yields a relatively simple array structure, make the ITD technique one of the most interesting tapering strategies for WPT arrangements.

To further improve the efficiency of such solutions, their combination with unequally spaced arrangements has been proposed as well [29]. In such a case, the same weighting function considered in (4) has been assumed, but the elements have been displaced by setting (5) shown at the bottom of the page (for the linear geometry) [29], and $y_n = 0$, where d is the basic element spacing, $\alpha_1 \in [0, 0.5]$ is (user-defined) size of a "nonuniform" region, and $A_1 \geq 0$ is the associated distortion factor (in general, $\alpha_1 \neq \alpha_0$ and $A_1 \neq A_0$) [29]. Thanks to such a choice, the arising isosceles-trapezoidal distribution with unequal element spacing (ITDU) arrangement has been shown to yield improved efficiencies with respect to both ITD and Gaussian arrays (e.g., $E_3^{\mathrm{ITD}} \approx 98.76\%$, $E_3^{\mathrm{Gauss}} \approx 98.33\%$, $E_3^{\mathrm{ITDU}} \approx 99.69$, when $N \approx 100$ [29, Table I]), at the expenses of a more complicated geometrical layout [29].

C. Synthesis Approaches Exploiting Optimization Tools

The previous approaches yield simple (i.e., easily computable whatever the array size) but suboptimal array weights [30]. To achieve higher performances, the application of optimization approaches [63], [64] to WPT design systems has been investigated over the last few years [30], [65]–[67].

An application of optimization approaches to WPT array design has been proposed in [67]. More specifically, a *coordinate descent* method has been introduced to find w_n, $n = 0, \ldots, N-1$, that maximizes the power transfer by matching a required field distribution $W_{\mathrm{REF}}(u, v)$ [67]. Toward this end, the minimization of the following functional [67]:

$$\Psi_{\mathrm{CD}} = \int_{\Omega} \left| \sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)} - W_{\mathrm{REF}}(u,v) \right|^2 du\, dv + \eta \left(\frac{\max_{(u,v)\notin\Omega+\Delta} \left(\sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)} \right)}{\max_{(u,v)\in\Omega} \left(\sum_{n=0}^{N-1} w_n e^{ik(ux_n+vy_n)} \right)} \right) \tag{6}$$

(Δ being the "zone of safety" surrounding the receiver area, and η being a weight factor) has been carried out through an iterative process based on the following steps [67]:

1) initialize $w_n = 1$, $n = 0, \ldots, N-1$, iteration number $h = 0$, and element number $p = 0$;

$$|w_n| = \begin{cases} A_0 + \dfrac{n(1-A_0)}{\alpha_0(N-1)}, & n \in [0, \alpha_0(N-1)) \\ 1, & n \in [\alpha_0(N-1), (1-\alpha_0)(N-1)] \\ 1 + (1-A_0)\dfrac{(1-\alpha_0)(N-1)-n}{\alpha_0(N-1)}, & n \in ((1-\alpha_0)(N-1), (N-1)] \end{cases} \tag{4}$$

$$x_n = \begin{cases} nd \times \dfrac{\mathrm{sinc}\left[A_1 + \frac{n(1-A_1)}{\alpha_1(N-1)}\right]}{0.8415}, & n \in [0, \alpha_1(N-1)) \\ nd, & n \in [\alpha_1(N-1), (1-\alpha_1)(N-1)] \\ nd \times \dfrac{\mathrm{sinc}\left[1 + (1-A_1)\frac{(1-\alpha_1)(N-1)-n}{\alpha_1(N-1)}\right]}{0.8415}, & n \in ((1-\alpha_1)(N-1), (N-1)] \end{cases} \tag{5}$$

2) minimize the functional Ψ_{CD} only with respect to $w_n|_{n=p}$ through a line search technique (1-D minimization);
3) if $p = N-1$, goto 4); else, update $p \leftarrow p+1$, and goto 2);
4) if $\Psi_{CD} \leq \overline{\Psi}$ terminate; else, update $k \leftarrow k+1$, $p = 0$, and go to 2);

where $\overline{\Psi}$ is the user-defined threshold on the functional value (used as a stopping criterion). Thanks to the considered approach, improved E_3 values have been achieved over standard Gaussian weighting, although at the expenses of a nonmonotone decrease of the amplitude distribution toward the edge of the transmitting aperture [67].

A different approach has been followed in [65] and [66] to design large WPT arrays with maximum transmission efficiency and controlled sidelobes. More in detail, the exploitation of a combined stochastic algorithm (CSA) has been proposed for the design of linear WPT transmitting arrangements with either equal ($w_n = 1, n = 0, \ldots, N-1$) or squared cosine weighting ($w_n = [\cos(\pi x_n/2)]^2$, $n=0,\ldots,N-1$) comprising nonuniformly spaced elements [65], [66]. Toward this end, the antenna positions have been computed as

$$x_n = nd + \delta_n \tag{7}$$

where δ_n is a small (with respect to d) random perturbation to be applied to each antenna position to (stochastically) optimize the sidelobe level and the beam collection efficiency (E_3) [66]. Such a technique has been shown in [65] and [66] to yield improved transmission efficiency and sidelobe level (SLL) control over standard uniform arrangements (e.g., $\mathrm{SLL}^{\mathrm{UNI}} = -13.5$ dB, $\mathrm{SLL}^{\mathrm{CSA}} = -35$ dB when $N = 16\,000$ [66]), while also enabling the design of very large layouts with a reduced computational efforts [66].

A further enhancement of such a technique has been investigated by considering the improved CSA (ICSA), which can be derived from the CSA simply by substituting (7) with the following element displacement rule [66]:

$$x_n = \nu_1 \times nd + \nu_2 \times \delta_n \tag{8}$$

where ν_1 and ν_2 are user-defined constants aimed at improving the layout performances (the tradeoff values of $\nu_1 = 0.93$ and $\nu_2 = 0.1$ were deduced in [66]). Indeed, in such a case, the average sidelobe level (ASLL) was shown to reduce from $\mathrm{ASLL}^{\mathrm{CSA}} = -42$ dB to $\mathrm{ASLL}^{\mathrm{ICSA}} = -58$ dB when $N = 16\,000$ [66].

Differently from [66], an iterative optimization technique has been followed in [30] to maximize the WPT transmission efficiency subject to a constraint on the sidelobe level [44]. More specifically, an evolutionary programming (EP) strategy [68] has been applied in [30] to design an arrangement complying with a low-sidelobe radiation mask $W_{\mathrm{REF}}(u,v)$ and with a maximum radiation efficiency. Toward this end, an EP algorithm comprising a "Levy" and a "Gaussian" mutation operator [68] has been employed to minimize the functional in (9), shown at the bottom of the page [30], where (u_q, v_q), $q = 0, \ldots, Q-1$, are the samples of the radiation pattern considered for the optimization, and $h(\cdot)$ is the Heaviside function. By means of such an approach, good performances in terms of E_3 and sidelobe-level control have been obtained for circular arrangements (e.g., $E_3^{\mathrm{EP}} = 0.963$, $\mathrm{SLL}^{\mathrm{EP}} = -40$ dB [30]), at the expenses of a quite large computational complexity for the antenna design [30]. Indeed, several thousand evaluations of (9) have been required to reach convergence in the examples in [30], as expected.

D. Theoretically Optimal Designs

Closed-form expressions for the maximization of the transmission efficiency (E_3) of WPT antenna arrays have been also derived in the literature [43], [44], [69]–[73]. Indeed, a direct optimization of the quantity E_3 can be carried out in closed form, at least in some specific cases [43], [44], [69]–[73]. The importance of these techniques is twofold: on the one hand, they provide the upper bound for the transmission efficiency achievable by an arbitrary arrangement, and therefore can be used as a "guideline" for the evaluation of suboptimal techniques [71]; on the other hand, they provide a reference solution which can be applied as a starting point for other methodologies [71]. Unfortunately, due to their computational complexity, and since the arising feeding network is in general more complicated than those obtained by the other techniques (e.g., a large set of different amplifiers are usually required, owing to the smooth nature of the obtained profiles), such approaches are usually employed only for compact arrangements.

The first techniques developed for the maximization of the WPT transmitting antenna efficiency have been concerned with continuous apertures [72], [73]. As an example, the optimal illumination for planar antennas of arbitrary shapes and sizes have been deduced in [72] by solving an eigenvalue problem formulated through an

$$\Psi_{\mathrm{EP}} = \left(-E_3 + \frac{\sum_{q=0}^{Q-1} h\left[W(u_q,v_q) - W_{\mathrm{REF}}(u_q,v_q)\right] \times \left[W(u_q,v_q) - W_{\mathrm{REF}}(u_q,v_q)\right]}{Q}\right) \tag{9}$$

integral equation similar to those derived for generalized confocal resonators [72]. Moreover, the explicit computation of the optimal illumination has been derived for the rectangular case, resulting in the product of prolate spheroidal wave functions [72]. Further developments aimed at taking into account constraints on the sidelobe level have been developed as well (by introducing conjugate-gradient approaches) [44]. The design of continuous layouts comprising subapertures has been addressed as well by means of the so-called matrix method [75].

Concerning antenna arrays, the optimal solution for maximizing E_3 in the linear case has been obtained [69], [70] by exploiting the so-called discrete prolate spheroidal sequences (DPSSs) [74]. Indeed, by rewriting E_3 for 1-D geometries $(y_n = 0)$ as

$$E_3 = \frac{\int_{-\omega}^{\omega}\left|\sum_{n=0}^{N-1} w_n e^{ik(ux_n)}\right|^2 du}{\int_{-1}^{1}\left|\sum_{n=0}^{N-1} w_n e^{ik(ux_n)}\right|^2 du} = \frac{\mathbf{w}^T \Xi \mathbf{w}}{\mathbf{w}^T \mathbf{w}} \tag{10}$$

$[\mathbf{w} = \{w_n, n = 0, \ldots, N-1\}$, $u \in [-\omega, \omega]$, being the size of the receiver region (in u coordinates), and Ξ being an $N \times N$ matrix whose (n, p) entry is equal to $\xi_{np} = \int_{-\omega}^{\omega} e^{iku(x_n - x_p)} du]$ it turns out that $\mathbf{w}$ maximizing E_3 is the eigenvector of Ξ corresponding to the maximum eigenvalue of the same matrix [69]. Thanks to such a property, the optimal WPT array synthesis is mathematically determined by solving an eigenvalue problem of size $N \times N$ [69], [74]. To help understand such a formulation, the calculation results obtained in the optimization of a $N = 41$ half-wavelength spaced array are reported in Fig. 5. More specifically, the DPSS patterns obtained through the procedure discussed in [69] have been computed by assuming $\omega \in \{0.1, 0.075, 0.05\}$ to point out the dependency of the mainlobe size, sidelobe level, and beam shape on the receiver region [Fig. 5(b)]. For completeness, the associated array weights are reported as well [Fig. 5(a)].

Starting from the above results, constrained synthesis problems aimed at maximizing E_3 by also taking into account sidelobe level, directivity, or signal-to-noise ratio constraints have been addressed through a modified eigenvalue method [43]. To simplify the computation of the optimal weights for large-size problems, approximate solutions (based on Kaiser weighting windows) have been discussed as well [70].

Similar approaches have been recently investigated also considering the planar case [51], [71]. However, the complexity of the 2-D optimal synthesis turns out to be significantly increased with respect to the linear one, both because of the inherently larger problem size and because of the nature of the eigenvalue problem to be solved, which turns out to be a generalized one [51], [71]. Accordingly, suitable simplifications (concerned with the calculation of the problem kernel) have been taken into account in such a case [51], [71]. More specifically, the calculation of the ξ_{np} elements has been carried out in [51] by assuming either rectangular or circular Ω regions, thus enabling the arising integral to be computed in closed form (i.e., avoiding expensive multidimensional numerical integrations). Thanks to such a choice, arrays comprising up to $N = 1600$ elements (yielding $E_3 \approx 99.98\%$) have been designed with a computational time of the order of 10^2 seconds on a desktop PC [51].

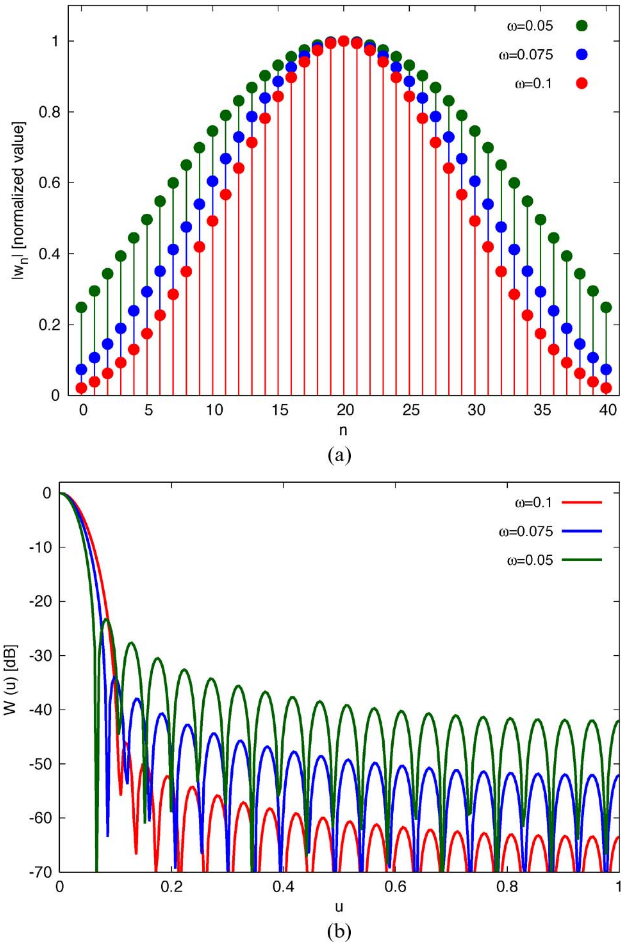


Fig. 5. *DPSS design $[N = 41, \omega \in \{0.1, 0.075, 0.5\}]$. (a) Optimal weights and (b) associated radiation patterns.*

E. Recent Advances and Future Trends

The design of WPT transmitting array is an active research area which is currently investigated by several research groups worldwide [17], [21], [26], [42], [54], [58], [76]. Owing to the main limitations of current methodologies, that is, the costs, complexity, weight, and ease of control of designed WPT arrays, most of present efforts are aimed at the following objectives:

- increasing the accuracy and robustness of retrodirective control techniques to enhance the safety and efficiency of power transfer;

- reducing the complexity of the feeding network while achieving efficiencies which are comparable to the theoretical optimal;
- decreasing the weight of the WPT array by means of nonregular architectures.

Concerning the first objective, approaches able to achieve enhanced performances with respect to the classical retrodirective beam methodologies have been recently investigated [26], [42], [54], [58], [71], [77], [78]. As an example, the position and angle correction (PAC) method [25], [42], [54] has been introduced with the aim of achieving an optimum beam focusing also in the presence of position drifts in paneled arrays (often occurring in large structures [42]). More in detail, the PAC algorithm requires the pilot signal sent by the receiver to be processed so that its phase is measured on each antenna panel [42]. Such an information is then used by each panel to calculate the DoA of the pilot wave, its own position, and its inclination (through the retrodirective method [25]) [42]. By combining such an information with those resulting from the other portions of the array, each subarray decides its position gap from the reference panel and corrects the phase deviation to suitably steer the overall beam [42]. As an example, a prototype of a retrodirective system based on the PAC algorithm has been demonstrated to yield an error $\leq 1^{\circ}$ in the phase compensation when using a 2.94-GHz pilot signal [25], [42], [79].

To further improve the accuracy of the retrodirective beam control, array calibration approaches targeted at WPT systems have been proposed as well [26]. More specifically, the rotating element electric field vector (REV) algorithm has been recently applied to calibrate a monopulse array used for WPT applications [26]. Thanks to such a step, a significant improvement in terms of steering accuracy and sidelobe control over the noncalibrated structure has been achieved [26].

Furthermore, it is worth noticing that alternative architectures employing Van Atta arrays [34] or switched beam layouts [80] have been investigated as well.

With reference to the second objective, the use of subarrayed configuration aimed at maximizing the antenna efficiency while reducing the feeding network complexity has been recently investigated through excitation-matching approaches [77], [78]. Toward this end, the contiguous partition method (CPM) [81]–[85] has been proposed for the synthesis of linear and planar arrangements matching DPSS excitations while comprising only few amplifiers [77], [78]. As an example, a $N = 128$ linear arrangement exhibiting a transmission efficiency equal to $E_3 \approx 89.7\%$ (for a collection area of size $\omega = 0.01$) has been obtained using only three different amplifiers, with a performance loss with respect to the theoretical optimum (using at least 64 amplifiers) of about 0.3% [77].

Moreover, the already proposed network simplification methods could be investigated and extended to WPT applications as well. For instance, in [86] and [87], a significant reduction of the number of the driven elements has been achieved by substituting some of them with passive dipoles. Such an approach has been shown to enable a 50% reduction of the network complexity with negligible performance losses in terms of synthesized pattern [87].

Concerning the third objective, sparse arrangements matching optimal (i.e., DPSS) patterns with as few radiating element as possible have been proposed to reduce the weight and complexity of WPT arrays [71], [78]. More specifically, Bayesian compressive sensing (BCS) techniques [88], [89] have been introduced to design sparse linear layouts able to achieve the same efficiency of DPSS arrangements but with a reduced number of antennas (e.g., a saving of 35% radiating elements has been shown in [78] for a target $E_3 = 95\%$), and on the other hand to increase the efficiency of DPSS layouts for a certain number of radiating elements [71], [78]. Moreover, the analysis of other array design techniques which are naturally sparse and may be appropriate for WPT, such as polyfractal [91] or raised-power-series [92] arrays, is still an open research topic.

IV. SYNTHESIS OF RECTENNA ARRAYS

The design of rectenna arrays is a fundamental problem to guarantee a satisfactory end-to-end efficiency in WPT systems [3], [5], [8], [16]. Although most of the research in this area has dealt with the design and manufacturing of single rectennas (suitable for handheld mobile applications) [3], [5], [8], [16], the displacement and combination in array architectures has gathered more and more attention in the last few years [33], [34], [90], [93]. Since arrays of equally weighted antennas are considered in reception (unlike the transmitting case) [8], attention will be mainly focused on the following design of the array geometry and power combination architecture [94].

A. Architectures Based on a Single RF-to-DC Converter

The design of a receiving antenna in a long-range WPT can be carried out starting from a classical phased array layout (possibly comprising focusing devices such as reflectors and lenses) connected to an RF-to-DC converter at its output port [Fig. 6(a)] [48], [93], [95]. Architectures of this kind are characterized by high reception efficiencies, since the impinging power is coherently summed [48]. Under such assumptions, the receiving antenna comprises an RF combining network which is responsible for the in-phase combination of the incoming waves [48], [93], [95]. Owing to this, such architectures require the receiving array to track the incident beam in real time, and therefore are more suitable for "fixed" (e.g., ground-to-ground) WPT applications.

As an example, a WPT receiving array comprising eight patch antennas connected to a single RF-to-DC converter

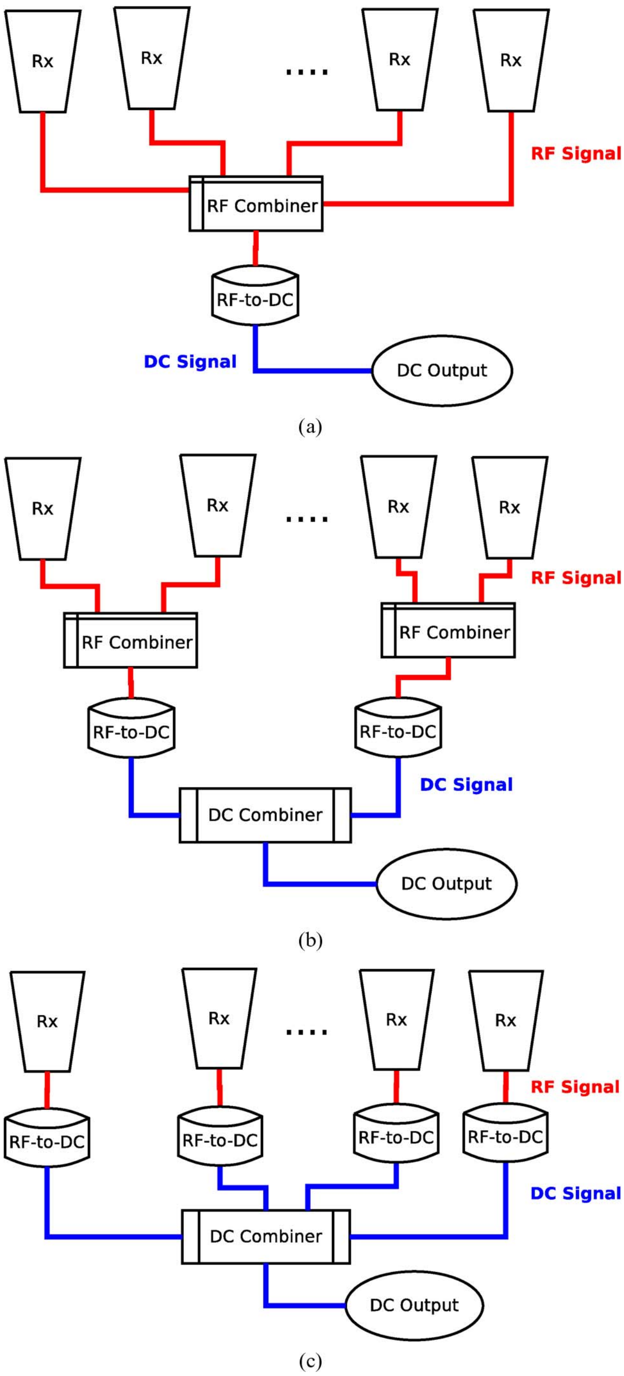


Fig. 6. ***Block diagram of receiving WPT arrays comprising (a) a single RF-to-DC combiner, (b) a subarray arrangement, and (c) a rectenna array.***

has been proposed in [95]. In such an application, a collecting arrangement has been designed for an 8-GHz compact application requiring high reception gain. Indeed, thanks to the considered arrangement, a 15.07-dBi broadside gain has been actually achieved by the rectenna arrangement, thus enabling a high end-to-end efficiency for the overall system [95]. Such performances have been further enhanced by introducing focusing reflectarray (achieving a total 18.60-dBi gain) [95]. Similarly, a 2×2 microstrip antenna array comprising a single diode has been demonstrated in [93], where an overall 6.8-dBi gain has been obtained at 2.45 GHz for the rectenna.

An analogous concept has been considered for the development of a WPT prototype recently completed by the authors and colleagues [Fig. 7(a)]. In such a prototype, a four-element dipole array working at 2.45 GHz is connected to an RF combining network, whose output signal is then sent to a single rectifying diode [Fig. 7(b)]. In order to increase the overall efficiency, a metallic reflector has been added to the receiving antenna [Fig. 7(a)], yielding an overall 75% efficiency in reception (i.e., $E_4 \times E_5$).

B. Subarray-Based Arrangements

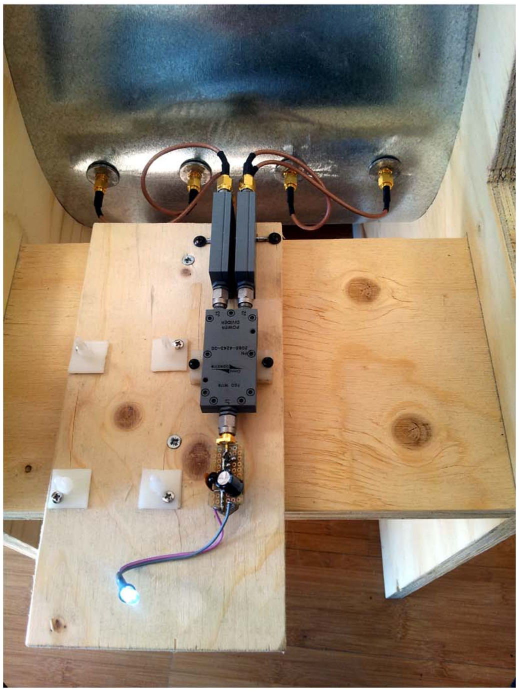
Unfortunately, receiving arrays including a single RF-to-DC converter have the disadvantage of requiring a full RF feed network (working at high power levels, possibly) able to track the transmitter beam. Moreover, they are less robust to diode failures, since the power conversion is carried out in a single collecting point. To reduce such drawbacks, subarray-based architectures have been proposed [Fig. 6(b)]. In these architectures, the overall receiving layout is divided into subarrangements whose gathered signals are (locally) combined in RF and then converted to DC [Fig. 6(b)]. Each subarray DC output is then connected to the overall combiner, which is responsible for the power summation [Fig. 6(b)]. Accordingly, a modular structure comprising one low-complexity RF network and an RF-to-DC converter for each subarray is obtained [Fig. 6(b)].

Following this guideline, in [32], a set of four folded dipole antennas (working at 5.8 GHz) has been combined in a dual-rhombic loop antenna (DRLA) subarray at the RF level, and linked to a single high-efficiency RF-to-DC circuit. The resulting subarray has been then replicated and combined in DC to synthesize an overall 4×16 receiving array [32]. Thanks to such a choice, a high collecting efficiency has been obtained ($E_4 \times E_5 \approx 82\%$) despite the simple RF combination network [32].

C. Combination of Rectenna-Collected Signals at the DC Level

The most widely deployed WPT receiving arrangement is based on the straightforward combination at the DC of the signals received and converted by each antenna [Fig. 6(c)] [31], [33], [34], [48], [94], [97]. The main advantage of such a choice is represented by its simplicity [31], [33], [48]. Indeed, no RF alignment is required throughout the receiving aperture because of the noncoherent combination of the received signals [Fig. 6(c)] [48], [49]. Accordingly, the antenna deployment, interconnection, and calibration are significantly simplified with respect to a phased array antenna [31]. Moreover, such a choice provides significantly enhanced DoFs for the

(a)



(b)

Fig. 7. ***Prototype of a rectenna array comprising a single RF-to-DC combiner developed at the ELEDIA Research Center. (a) The 4 $\times$ 1 dipole array comprising the truncated parabolic reflector. (b) Detail of the 4-to-1 RF combination network and of the RF-to-DC conversion board directly connected a testing load (i.e., a high-intensity LED).***

element displacement, as no phase correction is required [48], [49]. On the other hand, such an architecture yields a lower overall efficiency with respect to a coherent reception of the incident power, since the rectification is done on an element-by-element basis [31], [48]. In fact, assuming that (after phase compensation) the M receiving antennas have the same output signal $x(t)$, it turns out that $P_{\mathrm{OUT}}^{\mathrm{coherent}} \propto \lim_{T\to\infty}\{\int_{-(T/2)}^{T/2}[\sum_{m=1}^{M}x(t)]^2 dt/T\} = M^2 \times \lim_{T\to\infty}\{\int_{-(T/2)}^{T/2}[x(t)]^2 dt/T\}$ if coherent combination is at hand, while in a DC combination scheme $P_{\mathrm{OUT}}^{\mathrm{noncoherent}} = \sum_{m=1}^{M} P_{\mathrm{OUT}}^{\mathrm{DC-comb}}|_n \propto M\times \lim_{T\to\infty}\{\int_{-(T/2)}^{T/2}[x(t)]^2 dt/T\}$ (for instance, up to $\approx$3-dB loss was observed for a four-element broadside steered array in [48]). Furthermore, a careful choice of the DC combination architecture is required to avoid power losses [31], [33], [94].

Several prototypes have been demonstrated in the literature which comply with the architecture in Fig. 6(c). As an example, in [31], a receiving array comprising 48 $\times$ 48 rectennas has been developed and measured achieving a maximum RF-to-DC conversion efficiency (E_5) of about 50% (for an absorbed power $P_{\mathrm{RX}} = 1.2$ kW). Toward this end, each receiving antenna (microstrip printed dipole working at 2.45 GHz) has been linked to a rectifying circuit comprising 16 diodes [31]. The DC power resulting from each rectenna has been then combined assuming different series/parallel connection schemes, showing a nonnegligible dependency of the obtained efficiency on the architecture of the DC summation network (i.e., a variation of about 5% in E_5 has been observed for the different series/parallel layouts) [31], [94].

A similar architecture has been considered in [96] to produce a high-voltage (50 V) output. In such a case, nine dual-polarized patch antennas comprising an independent rectifying circuit for each polarization (i.e., 18 individual rectenna elements) have been combined through a series scheme, and E_5 50% has been experimentally observed at the operative frequency of 8.51 GHz [96].

The impact of the DC combination architecture on the array conversion efficiency has been investigated in detail in [33] and [34]. More specifically, the exploitation of series [Fig. 8(a)], parallel [Fig. 8(b)], and cascaded [Fig. 8(c)] networks to combine the signals received by each microstrip patch rectenna working at 5.8 GHz have been analyzed, deducing that cascaded rectenna arrays are more suitable for low-power WPT transmissions [33], while the lowest output power is obtained by the series connection [33]. Such results have been then employed for the realization of dual-patch, six-patch, and 16-patch rectenna arrays exhibiting a maximum 74% reception efficiency $(E_4 \times E_5)$ [33].

Similar approaches have been also employed for the design of WPT receiving systems comprising dual-rhombic loop rectennas [98]. More in detail, a set of 3 $\times$ 3 rectennas have been connected following the architecture in Fig. 6(c) to yield a high-gain and low-complexity receiver for WPT applications [98]. As a matter of fact, a 78% conversion efficiency $(E_4 \times E_5)$ at 5.61 GHz has been obtained by the prototype [98].

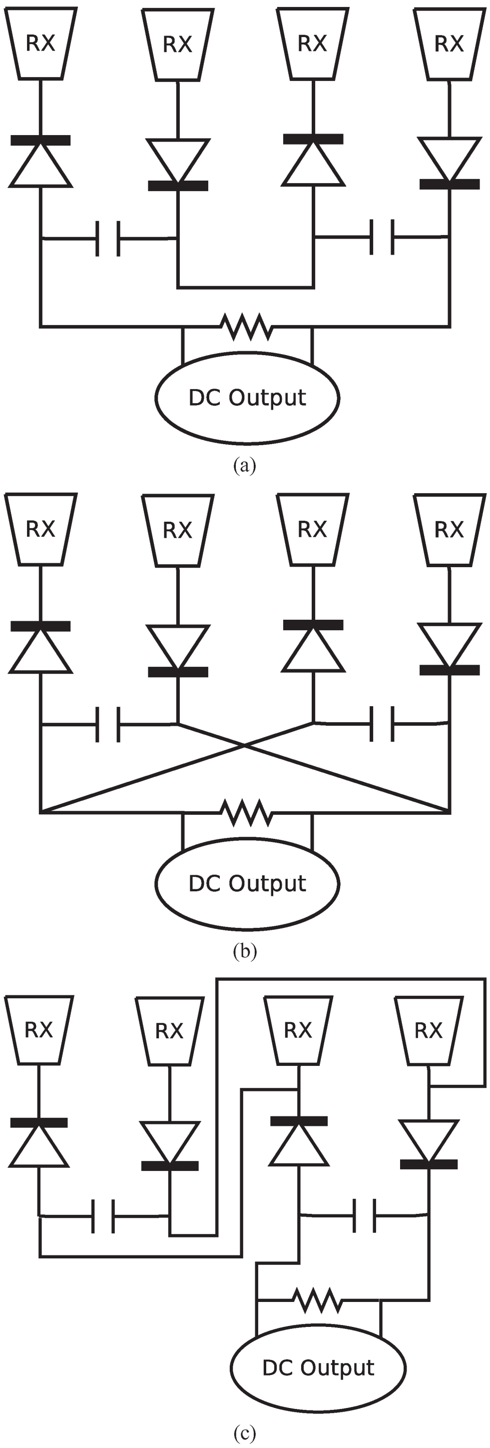


Fig. 8. ***Layout of rectenna array layouts from [33]. (a) Series. (b) Parallel. (c) Cascaded.***

D. Recent Advances and Future Trends

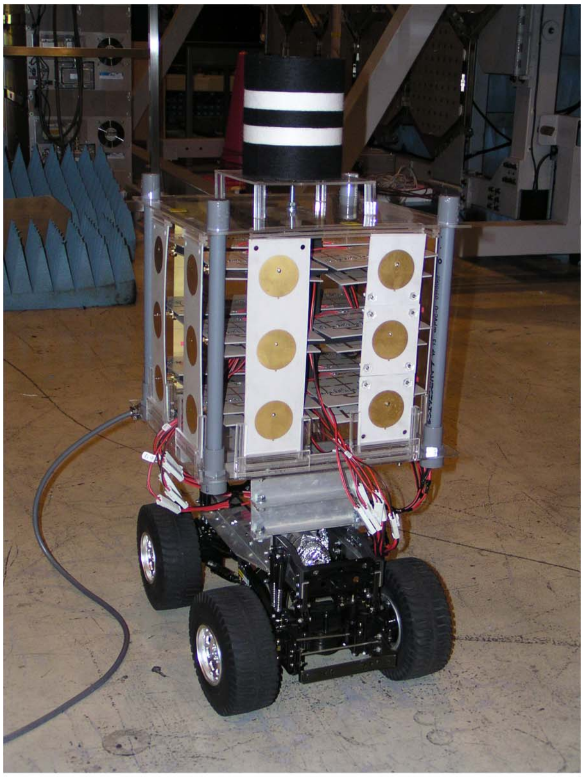
The study and development of improved rectenna arrays is currently one of the most important research areas in the field of WPT system design. Beyond the design and manufacturing of single rectennas, current research activities are aimed at overcoming the limitations of present-day WPT receiving architectures by means of more efficient power combination strategies [48], as well as more compact array structures comprising several elements [58], [99]. Moreover, the investigation of innovative array geometries exploiting the additional DoFs enabled by WPT applications are currently being investigated [49].

In this framework, innovative receiving network schemes for rectenna arrays have been proposed for power harvesting applications [48]. More specifically, the exploitation of a modified Greinacher rectifier has been proposed in [48] in combination with four Kock-type eroded patch antenna elements (working at 2.45 GHz) arranged in a compact 2×2 array configuration. Different RF-to-DC conversion architectures [Fig. 6(a) and (c)] have been then considered, showing that, in the absence of a steering network in reception, the Fig. 6(c) architecture yields the highest average efficiency whatever the angle of the incident beam [48].

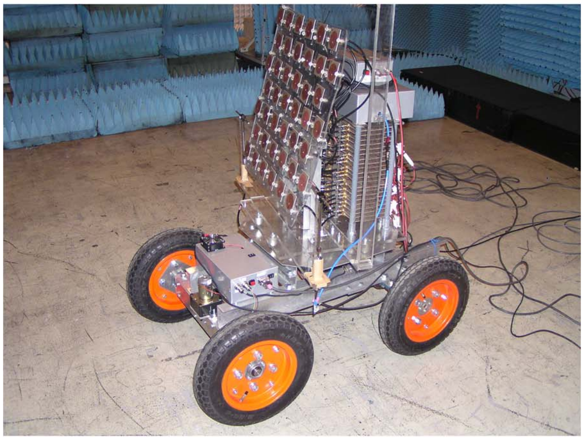
Concerning the reduction of the size of the WPT receiving array, a three-element compact rectenna architecture working at 9.3 GHz has been recently proposed [99]. More specifically, a 21% reception efficiency $(E_4 \times E_5)$ has been achieved by means of a planar arrangement comprising a slot antenna and a microstrip rectifying circuit [99]. Toward this end, the DC signals obtained by each antenna have been combined according to a cascade scheme [Fig. 8(c)] [99].

In the same line of reasoning, the development of compact rectenna arrays to be mounted on electric vehicles has been demonstrated in [20] (Fig. 9). In such a case, a rectenna structure has been designed by combining a circular patch with a high-power RF-to-DC converter comprising a four-way signal divider with parallel units of three high-efficiency diodes [20]. The output DC signals from each antenna have been then combined assuming the architecture in Fig. 6(c) to realize a four-plate structure comprising six circular microstrip antennas on each panel [Fig. 9(a)], or a mechanically steered single-plate rectenna with 42 circular patches [Fig. 9(b)] [20]. Thanks to the employed rectenna array, and despite the losses due to the nonoptimized transmitting arrangement and tracking [20], the vehicles have been successfully operated in a test field by using a 700-W generator working at 2.45 GHz, with an absorption of the engines between 5 and 35 W [20].

Finally, innovative design schemes are being analyzed which exploit the DoFs of noncoherent WPT receivers to increase their collection efficiency [49]. More specifically, by virtue of the fact that the relative positions of the single receiving antennas are irrelevant if a noncoherent combination scheme is adopted [Fig. 6(c)], a design scheme has been proposed in which the rectennas are suitably displaced to focus the array backscattered beam toward a mirror [49]. Since the backscattered contribution is again focused by the mirror toward the rectifying array, an increased collection efficiency can be achieved [49]. Toward this end, the design problem has been recast as an



(a)



(b)

Fig. 9. ***Prototypes of rectenna arrays mounted on WPT-fed vehicles [20]. (a) Four-plate rectenna comprising six circular microstrip antennas on each panel. (b) Single-plate rectenna with 42 circular patches.***

optimization one in which the power collected by the array elements is maximized through a suitable definition of the available DoFs (array element positions and mirror dimension and orientation) [49].

V. FINAL REMARKS

Long-range WPT is a promising technology for those application in which the transfer of energy over large distances in the absence of a wired electrical network is necessary or useful. Owing to the always increasing interest in such applications, several research activities concerning WPT systems are currently under development worldwide, and successful experiments have already been demonstrated. This is specifically true for the design of transmitting and receiving antenna arrays, because of their impact in the end-to-end performance of WPT systems.

In this paper, a review of the state-of-the-art array design techniques for long-range WPT has been presented. The latest advances and innovative solutions concerning the design of the transmitting array (i.e., beam shaping and beam steering problems; Section III) and of the receiver layout (a wave collection problem; Section IV) have been discussed, and some of the current trends and possible future frontiers of this research area have been analyzed.

The review has pointed out the following key issues and open problems in the design of long-range WPT arrays.

- The high efficient end-to-end WPT transmission requires an integrated design strategy concerning both transmitting and receiving arrangements. More specifically, suitable strategies to maximize the effectiveness of retrodirective beam focusing are of fundamental importance to enhance the safety and efficiency of WPT systems. In this scenario, cooperative solutions (also beyond those based on pilot signals from the receivers) are envisaged.
- Concerning the WPT transmitting arrays, designs including equally weighted elements turn out to be more effective in terms of costs and simplicity. However, a significant enhancement of the transmission efficiency is achievable by a suitable tapering of the aperture. Accordingly, currently studied simplified architectures able, on the one hand, to maximize the power transmitted toward the receiver area, and, on the other hand, to yield simple, robust, light, and inexpensive feeding networks are expected to provide major enhancements over first generation layouts.
- With reference to WPT receiving layouts, the choice of optimal array architectures and RF-to-DC conversion/power combination schemes represents a key aspect in the design procedure, and different tradeoffs are available depending on the target complexity, costs, and desired performances. While rectenna arrays with full DC power combination [Fig. 6(c)] are the most widely adopted scheme, a nonnegligible efficiency improvement is achievable by considering RF summation architectures [Fig. 6(a)]. However, such schemes need the development and implementation of tracking strategies also on the receiver side. Furthermore, the design and manufacturing of single rectennas as well as their optimal geometrical displacement still represent a vast research area which needs to be carefully investigated.

- Despite the efforts of the last few years (Fig. 1), several topics concerning WPT arrays are still at an initial phase of development, and a significant increase of the research activities in this field is envisaged. ■

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