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Review article

Wireless power transmission based on retro-reflective beamforming technique

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ABSTRACT

This review paper is on the retro-reflective beamforming technique for wireless power applications. The primary merit of retro-reflective beamforming technique is that wireless power transmission is augmented by radar tracking. Specifically, wireless power transmission is initiated by pilot signals broadcasted from wireless power receiver(s); and in response to the pilot signals, a wireless power transmitter delivers directional microwave power beams to the receiver(s). The microwave power beams follow the wireless power receivers' location dynamically as long as pilot signals are broadcasted periodically. The retro-reflective beamforming technique therefore has excellent potential to accomplish efficient wireless power transmission to non-stationary wireless power receivers. This paper reviews the basic principles and potential applications of wireless power transmission based on retro-reflective beamforming technique.

1. Overview of wireless power transmission and retro-reflective beamforming technique

Wireless power transmission is a broad topic. The focus of this paper is wireless power transmission to non-stationary targets (with "targets" standing for "wireless power receivers" throughout this paper), which is a sub-discipline of wireless power transmission. In Section 1.1, a few fundamental concepts relevant to wireless power transmission are discussed. Some wireless power transmission technologies are reviewed briefly in Section 1.2, and microwave power transmission is identified to be a superb candidate for supplying power to non-stationary targets wirelessly. Section 1.3 presents a brief narrative of how the retro-reflective beamforming technique could enable efficient microwave power transmission.

1.1. Wireless power transmission to non-stationary targets

Electricity has two practical meanings in our everyday life: Power and information. These two practical meanings can be readily illustrated by two outlets on the wall in every household. For example, a television set has cord connections with two outlets: One is a power outlet and the other is a cable TV outlet. From the television set's point of view, the power outlet is a source of power whereas the cable TV outlet is a source of information. The power delivery over power cord and the information delivery over cable TV cord can both be characterized by the physical quantity of Poynting vector, which is the cross product between the electric field vector and magnetic field vector [1]. Thus indeed, the power transmission over power cord and the information transmission over cable TV cord share the same physical nature. To be more specific, electrical power with high power level is propagating over the power cord, whereas electrical power with low power level is propagating over the cable TV cord. Obviously in the meantime, television signal is attached to the electrical power propagation over the cable TV cord, whereas no information/signal is attached to the electrical power propagation over the power cord. Correspondingly, the television set has an electrical power receiver at its inlet of power cord, and it has another electrical power receiver at its inlet of cable TV cord. Of course, the two electrical power receivers do not perform the same task. When electrical power is received by the television set from the power cord, part of the power is converted to optical power such that the television set's display is bright enough for human vision. When electrical power is received by the television set from the cable TV cord, the information/signal attached to the power is detached such that the television set knows what contents should be displayed.

Electrical information/signals can be transmitted by two possible means: Wired and wireless (it must be noted that DC signal cannot be transmitted wirelessly). For examples, landline telephone and cell phone embody wired voice signal transmission and wireless voice signal transmission respectively. Electrical power can also be transmitted either by wired means or by wireless means (as a note similar to DC

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Table 1
Practical applications of wired power transmission, wired information transmission, wireless power transmission, and wireless information transmission.

	Electrical power	Electrical information
Wired	Example of wired power transmission: Electricity distribution network 	Example of wired information transmission: Landline telephone 
Wireless	Example of wireless power transmission: Wireless charger for smartwatch 	Example of wireless information transmission: Cell phone 

signal, DC power cannot be transmitted wirelessly). The electricity distribution network (i.e., electricity grid) that supplies power to the society is the best example of wired electrical power transmission. As the practical applications of wireless power transmission, wireless chargers for electric toothbrushes, cell phones, and smartwatches are popular nowadays. While wired propagation and wireless propagation are based on the same physical laws (which are described by Maxwell's equations [1]), they are governed by different boundary conditions. Specifically, wired propagation follows the boundary conditions specified by transmission lines such as a piece of cable TV cord, whereas wireless propagation satisfies the boundary conditions dictated by the environments such as an urban environment.

On the basis of the discussions on "power versus information" and "wired versus wireless" above, four combinations are tabulated in Table 1, including wired power transmission, wired information transmission, wireless power transmission, and wireless information transmission. The wireless power transmission technology is not highly developed today, compared with the other three in Table 1. The four items in Table 1 rely on the same fundamental physics. Therefore, the wireless power transmission technology is as feasible as the other three in terms of fundamental physics. For instance, if strong power were broadcasted by a cell tower, one might receive sufficient wireless power to charge the battery of his/her cell phone. Nevertheless, the practical implementation of such a brute-force wireless power transmission is prohibitive due to a large number of practical restrictions. Three major practical concerns relevant to the wireless power transmission technology are discussed below.

Power transmission efficiency is the top concern pertinent to wireless power transmission. Power transmission efficiency is defined as the ratio between the value of received power and the value of transmitted power. When wireless power is delivered from a cell tower to a cell phone over a long distance (say, 200 m), the power transmission efficiency is very poor. Obviously, poor power transmission efficiency is equivalent to high financial loss. As a matter of fact, power transmission efficiency is an important metric in virtually every Electrical Engineering application, such as electricity grid and cellular communication, albeit wireless power transmission applications are particularly sensitive to the value of power transmission efficiency.

As the second practical concern, the wireless power transmission technology will not be accepted by the general public if it is not safe, that is, if wireless power transmission may cause biological hazards to human beings. While the potential hazards of wireless cell phone signals are still under study, it would be simply unacceptable for a cell tower to boost its broadcasting power in order to charge the battery of a remote cell phone. In fact, a range of regulations have been established to safeguard human safety from excessive exposure to wireless technologies [2,3].

Electromagnetic compatibility is the third vital concern the wireless power transmission technology must take into account. As one example of electromagnetic compatibility, there is a National Radio Quiet Zone in the United States, in which cell phone service is strictly limited in order to protect radio astronomical measurements from possible interferences [4]. Apparently, wireless power transmission applications are anticipated to create stronger interferences than wireless signal transmission applications (cell phone communication, for instance). As a result, the development of wireless power transmission technology must comply with laws/regulations enforced by the government, such as those issued by the Federal Communications Commission of the United States [5].

The practical concerns discussed above do not appear highly challenging when the target (i.e., wireless power receiver) is stationary at a fixed location. One of the classic demonstrations of wireless power transmission to a stationary target is shown in Fig. 1. In 1975, an experiment carried out by NASA JPL at the Goldstone Deep Space Communications Complex, California demonstrated the delivery of 30 kW of wireless power over one mile, i.e., 1.6 km [6,7]. As shown in the photo of Fig. 1, a narrow power beam was constructed by a large parabolic antenna toward a stationary wireless power receiver one mile away. Since the target is stationary and the path of wireless power transmission is fixed, it is possible to achieve high power transmission efficiency and avoid the potential hazards without tremendous technical difficulties.

When the target is not stationary or when its location is not fixed, the practical difficulties associated with accomplishing efficient and safe wireless power transmission increase significantly, compared with the scenarios of stationary targets. As a matter of fact, the rapid development of mobile technologies over the past few decades creates vital demand for wireless power transmission to mobile targets. Suppose an electronic tag is attached to each piece of merchandise in a supermarket; the total number of tags the supermarket staffs must deal with would be on the order of millions or ten millions. In front of such a large number of mobile/portable devices, wired charging would be practically impossible. Three specific applications of wireless power transmission to non-stationary targets (including charging electronic tags wirelessly) are narrated in Section 3.

1.2. Microwave as the carrier of wireless power transmission to non-stationary targets

Numerous wireless power transmission technologies have been proposed and are under research currently. This subsection does not intend to review the existing technologies comprehensively. Instead, with "wireless power transmission to non-stationary targets" as the goal, the available technologies are assessed and microwave power transmission is identified to be an excellent candidate.

Today, the term "wireless communication" usually refers to transmitting electrical information without using wires/cables (such as in cell phone communication applications), although wireless communication could be fulfilled in non-electrical forms (for instance, the everyday verbal conversation among people is a wireless communication in non-electrical form). Similarly, "wireless power transmission" typically stands for transmitting electrical power without using wires/cables, whereas wireless power transmission does not have to be carried out in the electrical form. For example, many researchers are interested in employing acoustic waves to accomplish wireless power transmission [8]. In acoustic power transmission, electrical power is converted to acoustic power at the transmitter, then the acoustic power propagates to the receiver, and finally the receiver converts the acoustic power back to electrical power. As far as the theme of this paper is concerned (which is wireless power transmission to non-stationary targets), acoustic power transmission does not appear highly advantageous. For instance, Section 3.2 of this paper is pertinent to wireless power transmission in outer space, in which scenario acoustic propagation is absent. Acoustic power transmission is particularly appealing in certain media (such as conductive media like human organs and tissues) where wireless transmission in the electrical form may suffer from heavy attenuation. As the applications of delivering wireless power to embedded/implanted devices are not of major interest for the purpose of this paper, this paper places emphasis on "transmitting wireless power in the electrical

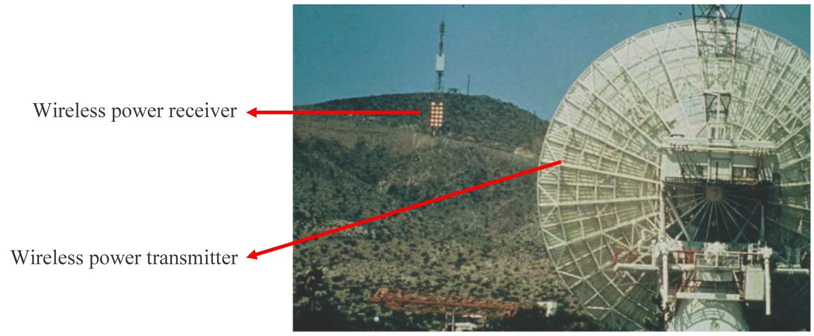
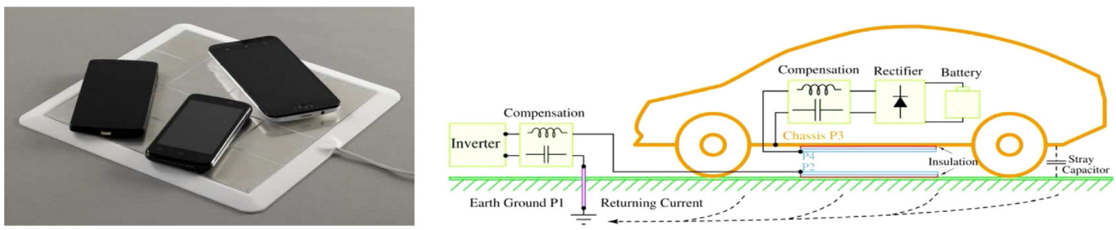


Fig. 1. A photo of 1975 Goldstone demonstration, in which wireless power was delivered from a stationary transmitter to a stationary receiver.



(a) Wireless charging based on low-frequency magnetic field

(b) Wireless charging based on low-frequency electric field

Fig. 2. Wireless power transmission technologies based on low-frequency magnetic fields and electric fields.

form" rather than "transmitting wireless power in the acoustic form". It is worth noting that, however, the basic principles of retro-reflective beamforming technique discussed in this paper are applicable to not only electromagnetic waves but also acoustic waves.

The technologies for transmitting power in the electrical form wirelessly can be roughly classified into the following three categories.

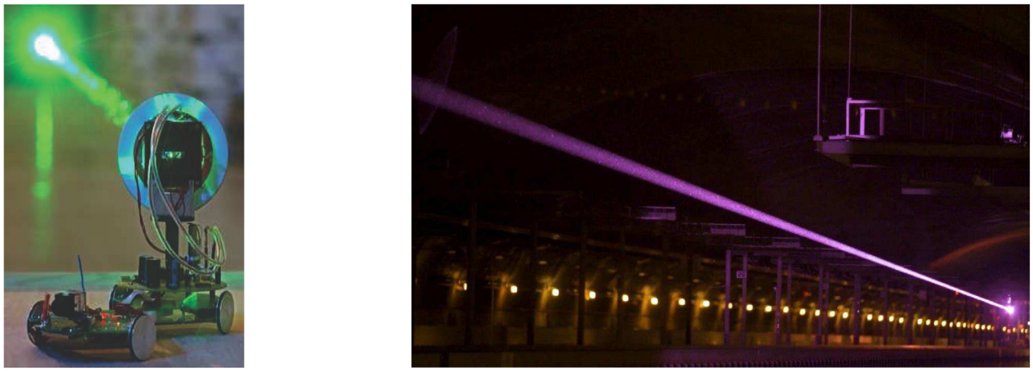
(i) Technologies based on low-frequency (below 100 MHz, typically) magnetic fields or electric fields.
(ii) Technologies based on high-frequency (above 100 MHz, typically) electromagnetic waves in microwave, millimeter wave, and Terahertz frequency bands.
(iii) Technologies based on optical waves such as infrared laser and visible laser.

Next, these three categories of technologies are discussed separately.

Inductive coupling is the best-known wireless power transmission technology [9]. Various products based on inductive coupling are commercially available. As an example, wireless charging pads for cell phones shown in Fig. 2(a) are popular nowadays. The inductive coupling technology relies on low-frequency magnetic field to achieve the coupling between a wireless power transmitter (such as a wireless charging pad) and a wireless power receiver (such as a cell phone) [10]. Since low-frequency magnetic field and low-frequency electric field are dual to each other in physics, it is unsurprising that capacitive coupling is able to achieve wireless power transmission as well. For instance, many researchers are endeavoring to charge electric vehicles wirelessly using low-frequency electric field as demonstrated by Fig. 2(b) [11]. The coupling efficiency based on low-frequency magnetic field or electric field drops quickly with the increase of distance. Consequently, the mobility of mobile devices (like cell phones and electric cars) are highly limited when they are charged, as depicted in Fig. 2. In order to charge mobile/portable target devices without limiting their mobility in practice, it appears that the wireless charging apparatus has to be bulky and intricate [12–14].

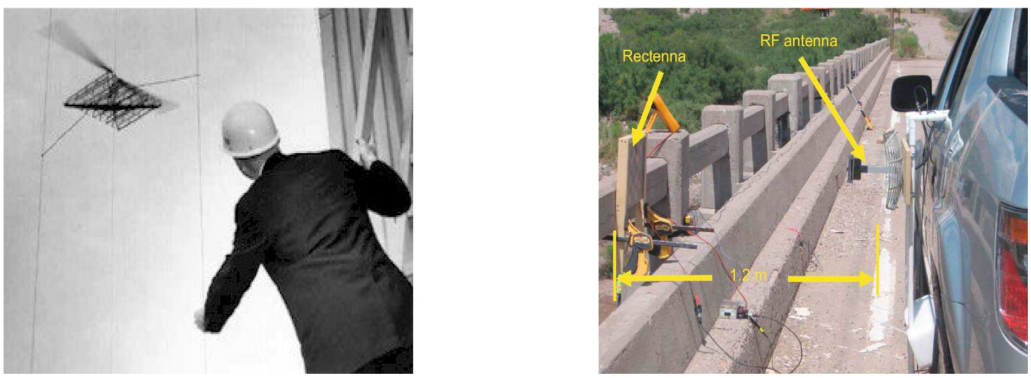
Laser propagation is highly directional and thus could carry wireless power over long distances. Two experimental demonstrations of laser power transmission are displayed in Fig. 3. The demonstration in Fig. 3(a) was conducted by a group of German researchers in 2004, in which wireless power was delivered to a rover vehicle through laser [15]. In October 2019, the Naval Research Laboratory demonstrated laser power beaming to the general public at Bethesda, Maryland for three days; as shown in Fig. 3(b), 400 Watts of laser power traveled over 325 m. Although it is possible for laser power transmission to reach long distance, optical waves suffer from poor penetration capability and poor conversion efficiency between electrical power and optical power. As far as wireless power transmission to non-stationary targets is concerned, a laser beam, as the carrier of wireless power, is required to be steered in real time to keep track of non-stationary targets' location. Though the most straightforward resolution is mounting a laser transmitter over a turn table and then steering the laser beam's direction mechanically, it is obviously not the optimal in practice. Numerous techniques of steering laser beams without resorting to mechanical motion (i.e., steering laser beams by electronic means) are under research [16,17], but are not as mature as the phased array technique for steering radio-wave beams.

Compared with low-frequency regime (i.e., below 100 MHz) and optical regime (i.e., above infrared), the frequency range in between them is an excellent candidate to accomplish efficient wireless power transmission to non-stationary targets. Enormous research efforts have been reported on employing microwave, millimeter wave, and Terahertz wave frequency bands for wireless power transmission [18–20]. Directional electromagnetic beams can be constructed in these frequency bands, which are analogous to laser beams. More importantly, phased array technique is well developed to steer the electromagnetic beams via electronic control signals, that is, without any mechanical motion. Beam steering or beamforming by electronic means enables keeping track of non-stationary targets in real time, maintaining high power transmission efficiency, and avoiding possible hazards. Particularly, the focus of this paper is wireless power transmission based on microwave carriers. Relative to millimeter wave and Terahertz wave, microwave offers better penetration capability and less vulnerability to atmospheric constituents. In addition, a large number of low-cost and mature fabrication process, components, and circuit schemes are readily available in the microwave frequency band for beam steering



(a) A demonstration in 2014 (b) A demonstration in 2019

Fig. 3. Wireless power transmission technologies based on optical waves.



(a) A demonstration in 1965 (b) A demonstration in 2009

Fig. 4. Two demonstrations of microwave power transmission technology.

or beamforming. Generally speaking, microwave appears more appropriate for wireless power transmission applications than millimeter wave or Terahertz wave, although the situation may evolve with the development of technologies in the future.

Microwave-based wireless power transmission technology, or simply microwave power transmission technology, has a rich history. As a far-from-exhaustive review of the history of microwave power transmission, several historical experiments are highlighted next. In the 1960s, Brown demonstrated supplying microwave power from a ground station to a helicopter (shown in Fig. 4(a)), which is probably the first impactful and well-documented demonstration of microwave power transmission in history [21]. In an experiment carried out at the laboratories of Raytheon in 1975, 54% of power transmission efficiency was measured [22]. The famous Goldstone demonstration in Fig. 1 was also conducted in 1975 [6,7]. The Stationary High Altitude Relay Program (SHARP) initiated in Canada in the 1980s aimed to provide microwave power to small aircrafts [23]. A program similar to SHARP, named MIcrowave Lifted Airplane eXperiment (MILAX), was active in Japan in the 1990s [24]. In 1993, International Space Year-Microwave Energy Transmission (ISY-METS) experiments were conducted in Japan to achieve microwave power transmission between spacecrafts [25]. A case study from 1997 to 2004 is reported in [26] to construct a point-to-point wireless electricity transmission to a small isolated village called Grand-Bassin in France. In 2009, the feasibility of using a car-borne power broadcaster to power sensors installed over a bridge was studied in [27], as demonstrated by a photo in Fig. 4(b). In the 2010s, a range of experiments of microwave power transmission on the ground as well as from ground to a drone were reported [18]. At present, quite a few companies are endeavoring to develop commercial products of microwave power transmission [28–31].

The retro-reflective beamforming technique has the potential to accomplish efficient microwave power transmission to non-stationary targets subject to the various practical concerns, as it includes the following two technical elements. First, a directional power beam is generated. Second, the power beam could be steered electronically in real time to aim at a non-stationary target. The theory and implementation of retro-reflective beamforming technique are studied in the rest of this paper.

1.3. Retro-reflective beamforming for microwave power transmission

This subsection presents a brief narrative of the retro-reflective beamforming technique for microwave power transmission to non-stationary targets. The specific technical principles of retro-reflective beamforming are elucidated in Section 2.

Retro-reflectivity has widespread applications in numerous disciplines, whereas its basic concept can be understood readily in optics. In Fig. 5, the difference between ordinary reflectivity and retro-reflectivity is illustrated using optical waves. When an incident light ray impinges upon an ordinary surface, the reflected light ray's direction is determined by both the incident light ray's direction and the direction normal to the surface. For a retro-reflective surface, however, the direction of reflected light ray always follows the direction of incident light ray and does not depend on the direction normal to the retro-reflective surface.

One of the applications of retro-reflectivity in optical engineering is traffic signs, as demonstrated in Fig. 6. When a car sheds light onto a traffic sign at night, the reflected light is desired to be returned to the driver rather than toward any other directions. Therefore, traffic signs made of retro-reflective surface appear more bright/visible at night.

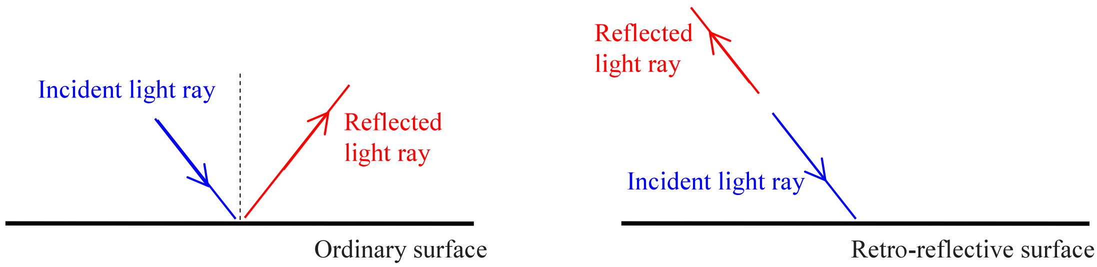


Fig. 5. An ordinary surface versus a retro-reflective surface in optics.

Fig. 6. Traffic signs made of retro-reflective surface appear bright at night.

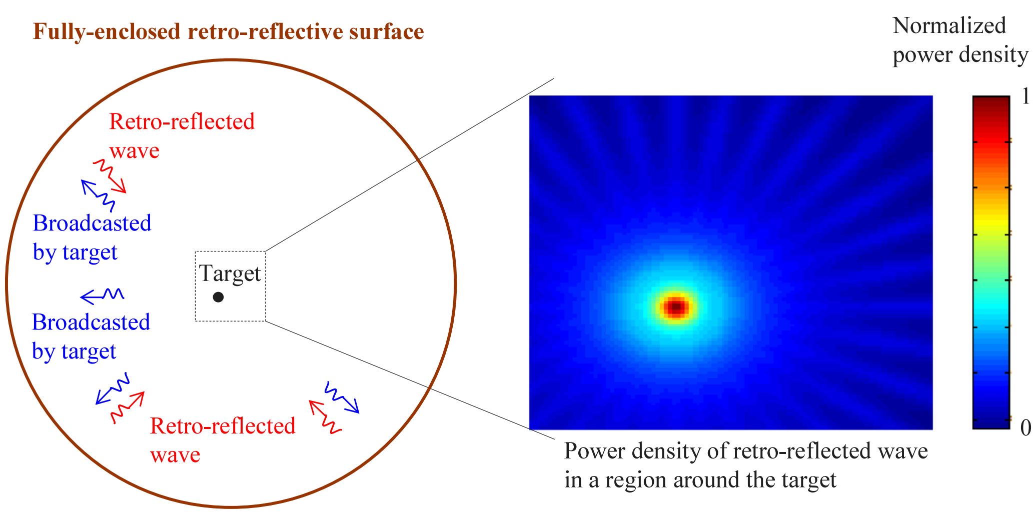


Fig. 7. Conceptual illustration of retro-reflective beamforming technique.

The retro-reflective beamforming technique is inspired by the concept of retro-reflectivity. As illustrated in Fig. 7, suppose a point target emits waves toward all the directions in the space. If a fully-enclosed retro-reflective surface is built around the target, the retro-reflected waves would converge onto the target's location.

If the retro-reflective surface in Fig. 7 is active, i.e., if the retro-reflective surface is attached to a power supply, the retro-reflected waves would be stronger than the waves broadcasted by the target. The resultant retro-reflective beamforming scheme has the potential to achieve efficient wireless power transmission. When a certain target is in need of wireless power, it broadcasts a signal toward all the directions as "request for wireless charging;" in this paper, the signal as "request for wireless charging" is termed *pilot signal*. When the pilot signal hits the retro-reflective surface, the retro-reflected waves are employed as the carrier of wireless power. As shown in Fig. 7, the spatial distribution of wireless power carried by the retro-reflected waves demonstrates a focal point at the target. In other words, the wireless power transmission resulted from retro-reflective beamforming is dedicated to the target in space. Obviously, the spatially-dedicated wireless power transmission displayed in Fig. 7 is the key to address the efficiency, safety, and electromagnetic compatibility issues raised in Section 1.1. In terms of power level, the retro-reflected waves are much stronger than the pilot signal. Overall, when retro-reflective beamforming technique is applied to accomplish wireless power transmission, the propagation of wireless power is guided or "ushered" by the propagation of pilot signal.

An active retro-reflective surface can be implemented by an antenna array in the microwave frequency band. Thus, it is practically viable to achieve efficient microwave power transmission by using the retro-reflective beamforming technique. The retro-reflective beamforming technique for microwave power transmission is illustrated in Fig. 8. The wireless power transmitter includes one or more than one antenna arrays (the antenna arrays are assumed to be composed of planar antenna elements in Fig. 8). A target (i.e., a wireless power receiver) receives wireless power from the wireless power transmitter via the following two steps.

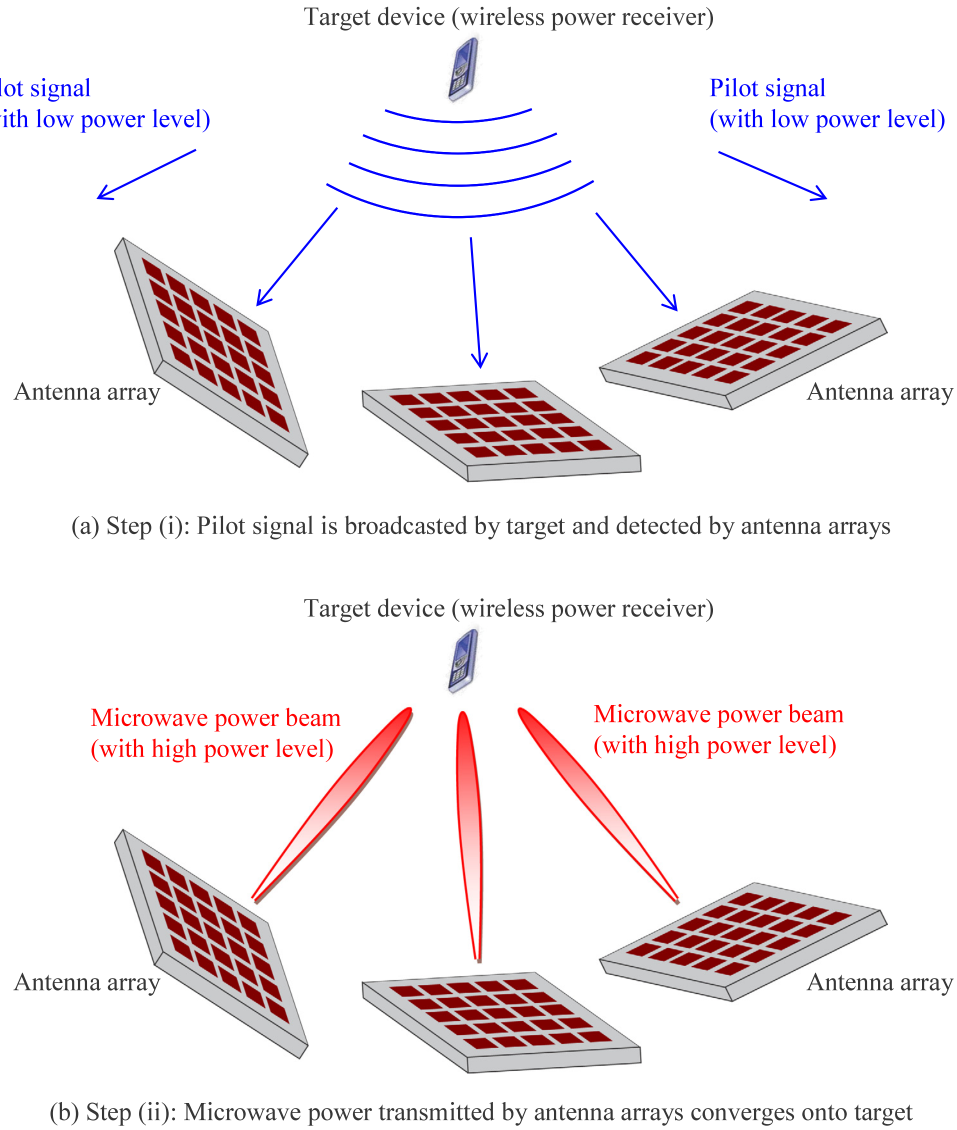


Fig. 8. Two-step scheme of retro-reflective beamforming for wireless power transmission.

Step (i) The target broadcasts a pilot signal. The pilot signal is received and analyzed by the antenna array(s) of wireless power transmitter.

Step (ii) Based on the outcome of analyzing the pilot signal, the antenna array(s) construct focused microwave power beam(s) onto the location of target.

Section 2 provides a technical description of the two-step scheme above.

When retro-reflective beamforming is applied to wireless power transmission, the microwave power beam(s) would follow the target's location dynamically as long as the target periodically broadcasts pilot signals. Intuitively, the larger the antenna arrays' aperture is, the better the performance of wireless power transmission would be (although building a fully-enclosed retro-reflective surface as depicted in Fig. 8 using antenna arrays is prohibitive in practice). It should be noted that retro-reflective beamforming has widespread applications (in wireless communication and radar, for instances), albeit this paper focuses on wireless power transmission applications.

2. Technical principles of retro-reflective beamforming technique

As pointed out in Section 1.3, an active retro-reflective surface can be implemented by an antenna array in the microwave frequency band. The technical principles of employing an antenna array to accomplish retro-reflective beamforming for microwave power transmission is illustrated in Fig. 9. In Fig. 9, a wireless power transmitter includes an array of N antenna elements deployed along the x direction and z direction. The antenna elements are assumed to be planar antenna elements (such as microstrip antennas and slot antennas) printed over a printed circuit board. A target (i.e., a wireless power receiver) has one antenna element. The target receives wireless power from the wireless power transmitter via the following two steps.

In the first step of retro-reflective beamforming, assume the target broadcasts a time-harmonic pilot signal at frequency f, as shown in Fig. 9(a). The pilot signal is received and analyzed by all the antenna elements of the wireless power transmitter. Suppose the pilot signal excitation applied at the circuit port of the target antenna has phasor value of 1 (that is, the amplitude value is 1 and phase value is 0). The pilot signal received at the circuit port of the wireless power transmitter's nth antenna element is denoted by phasor $H_{nt} = A_n e^{j\alpha_n}$, $n = 1, 2, \ldots, N$, with $j = \sqrt{-1}$. H_{nt} represents the wireless channel from the target to the nth antenna element.

In the second step of retro-reflective beamforming (Fig. 9(b)), the nth antenna element of wireless power transmitter is excited by a time-harmonic signal at frequency f with phasor $C(H_{nt})^* = CA_n e^{-j\alpha_n}$, $n = 1$, $2, \ldots, N$, where the superscript "*" is the complex conjugate operator.

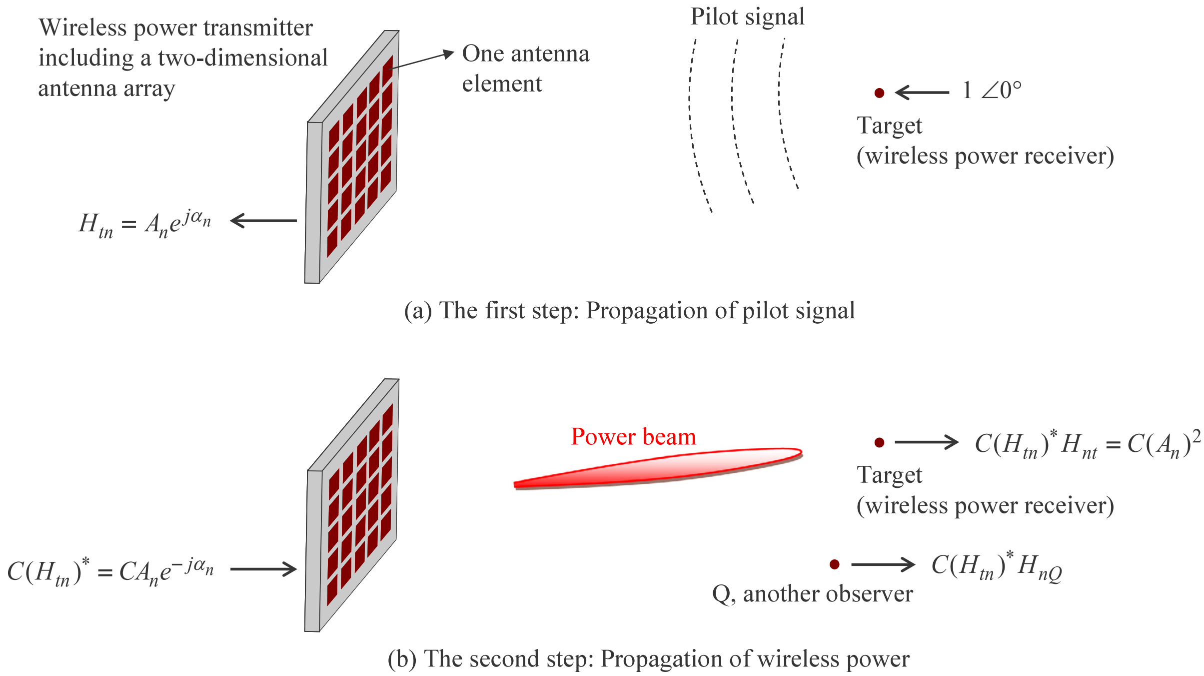


Fig. 9. Illustration of an antenna array as an active retro-reflective surface.

The constant "C" is much greater than 1 in practice, such that the wireless power propagation in the second step has much stronger power level than the pilot signal propagation in the first step. The wireless power transmitted by the nth antenna element would reach the target via the wireless channel of H_{tn} (i.e., from the nth antenna element to the target). Under the condition that the wireless channel between the target and the nth antenna element is reciprocal, H_{tn} and H_{nt} are identical to each other. The wireless power transmitted by the nth antenna element and received by the target is $C(H_{nt})^* H_{tn} = C(A_n)^2$, which is purely real-valued. Under the condition of reciprocity, the N antenna elements' wireless power radiations are constructive when they reach the target as they all end up with phase of zero at the target. Suppose there is another observer at Point Q (shown in Fig. 9(b)). The wireless power transmitted by the nth antenna element and detected at Point Q is $C(H_{nt})^* H_{Qn}$, where H_{Qn} represents the wireless channel from the nth antenna element to Point Q. It is very unlikely that the phase of $C(H_{nt})^* H_{Qn}$ is zero. More importantly, the wireless power radiations from the N antenna elements end up with different phase values at Point Q, and thus they are not fully constructive at Point Q. Consequently, the sum of the N antenna elements' wireless power radiations is stronger at the target than at Point Q. The spatial distribution of wireless power therefore exhibits a focal point at the target's location.

The core of the two-step scheme above is the phase conjugation relationship between pilot signal reception and wireless power excitation. Therefore, the retro-reflective beamforming technique is also termed as "phase conjugation antenna array technique". The phase conjugation relationship can be easily appreciated if the wireless power transmitter and wireless power receiver are in each other's far zone and if the only interaction between them is the line-of-sight interaction, although the fundamental principles of retro-reflective beamforming remain valid in the near zone or with multi-path [32]. When the pilot signal transmitter (which is the wireless power receiver) is far away from the wireless power transmitter, the pilot signals detected by the wireless power transmitter's antenna elements share the same amplitude. Meanwhile, the phase profile of pilot signals detected by the wireless power transmitter's antenna elements exhibits linear patterns along both x and z directions when there is no multi-path. According to the theory of phased array, the two-dimensional antenna array of wireless power transmitter would generate a beam if the array elements are excited by uniform amplitude and linear phase profile. When the phase profile of wireless power excitation is negative to the phase profile of pilot signal reception mathematically, the wireless power beam's direction is toward the wireless power receiver, from which the pilot signal stems.

Before the end of this section, the technical principles of retro-reflective beamforming is interpreted more rigorously by a circuit model.

The interaction between the wireless power transmitter and wireless power receiver in Fig. 9 can be modeled as a circuit network with (N + 1) circuit ports. As depicted in Fig. 10, the (N + 1) ports correspond to the circuit terminals of (N + 1) antenna elements respectively. The N circuit ports of wireless power transmitter's antenna elements are numbered "Port 1", "Port 2", "Port 3" ...., and the circuit port of the wireless power receiver's antenna is defined as "Port t" (with "t" standing for "target").

Suppose all the electrical signal or electrical power transmitted between the wireless power transmitter and wireless power receiver is time harmonic at frequency f. The circuit network in Fig. 10 can be described by scattering parameters as

$$\begin{bmatrix} b_t \\ b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{tt} & S_{t1} & S_{t2} & S_{t3} & \cdots & S_{tN} \\ S_{1t} & S_{11} & S_{12} & S_{13} & \cdots & S_{1N} \\ S_{2t} & S_{21} & S_{22} & S_{23} & \cdots & S_{2N} \\ S_{3t} & S_{31} & S_{32} & S_{33} & \cdots & S_{3N} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{Nt} & S_{N1} & S_{N2} & S_{N3} & \cdots & S_{NN} \end{bmatrix} \times \begin{bmatrix} a_t \\ a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_N \end{bmatrix} \quad (1)$$

As illustrated in Fig. 10, $a_t, a_1, a_2, \ldots, a_N$ are the incoming waves and $b_t, b_1, b_2, \ldots, b_N$ are the outgoing waves at the corresponding ports. The terms starting with "S" in (1) are the scattering parameters.

In the first step of retro-reflective beamforming, a time-harmonic pilot signal at frequency f is transmitted from the wireless power receiver to the wireless power transmitter, as displayed in Fig. 11. The pilot signal is supplied to the wireless power receiver's antenna element from an oscillator. Each antenna element of the wireless power transmitter is connected to a pilot signal analyzer (which are not shown in Fig. 11). Suppose the incoming wave at "Port t" is a_t. Also, suppose the N pilot signal analyzers are matched to the corresponding antenna elements respectively, such that $a_1 = a_2 = \cdots = a_N = 0$. The pilot signals

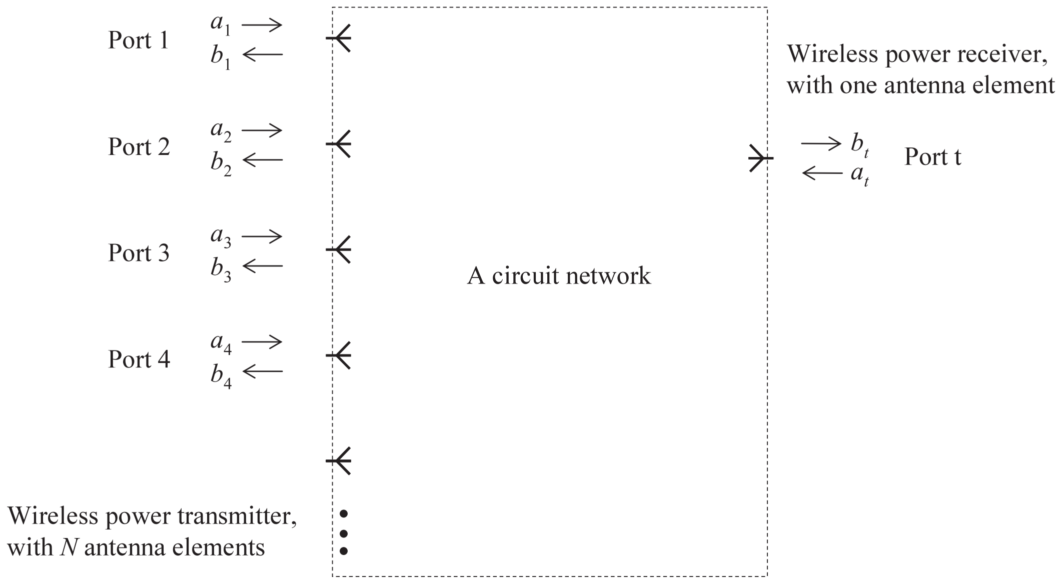


Fig. 10. A circuit model of retro-reflective beamforming for wireless power transmission.

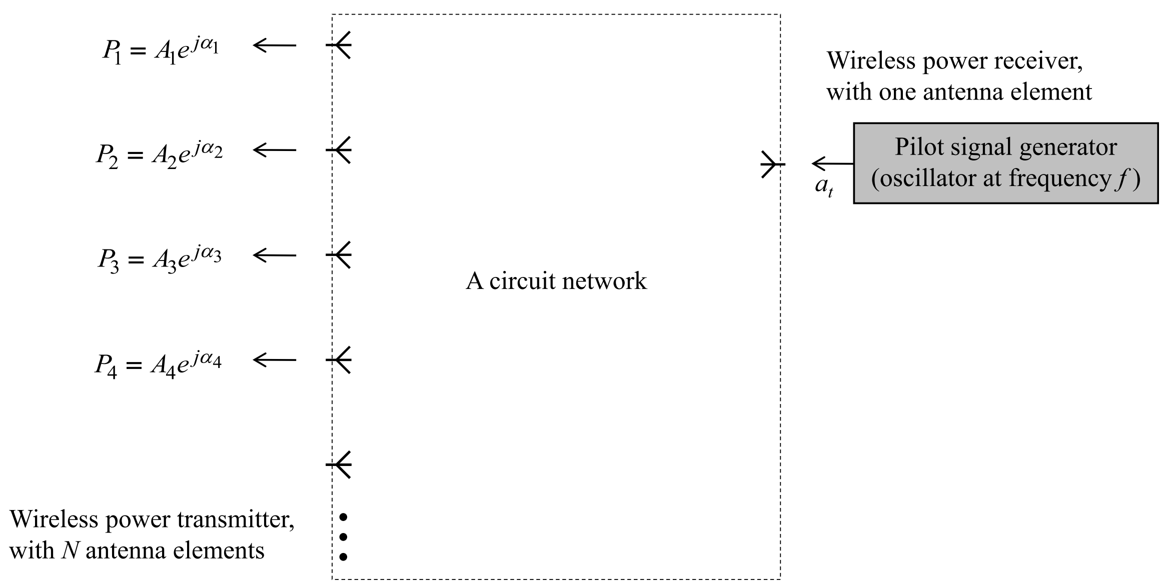


Fig. 11. Analysis of time-harmonic pilot signal propagation.

detected by the N pilot signal analyzers are denoted as P_n, $n = 1, 2, 3, \ldots, N$. The detected pilot signal P_n, which is the outgoing wave at Port n, can be found from (1):

$$P_n = S_{nt} a_t, n = 1, 2, 3, \ldots, N. \tag{2}$$

Furthermore, denote $P_n = A_n e^{j\alpha_n}$. In other words, A_1, A_2, A_3, $\ldots A_N$ represent the amplitude of the N pilot signals detected by the wireless power transmitter, and α_1, α_2, α_3, $\ldots$, α_N represent the phase values of the N pilot signals.

In the second step of retro-reflective beamforming, wireless power is transmitted from the wireless power transmitter to the wireless power receiver. As illustrated in Fig. 12, the incoming wave supplied to nth antenna element of wireless power transmitter is denoted as $X_n e^{j\psi_n}$, $n = 1, 2, 3, \ldots, N$, where X_n is the amplitude and ψ_n is the phase. The wireless power receiver's antenna is terminated by a matched load, such that $a_t = 0$. Due to (1), the outgoing wave b_t at "Port t" is

$$b_t = \sum_{n=1}^{N} S_{tn} (X_n e^{j\psi_n}). \tag{3}$$

Apparently, $|b_t|^2$ embodies the wireless power delivered to the wireless power receiver and ought to be maximized in practice. Mathematically, the right-hand-side of (3) constitutes an inner product between two vectors: One of them is $[S_{t1} \quad S_{t2} \quad S_{t3} \quad \cdots \quad S_{tN}]$ and the other is $[(X_1 e^{j\psi_1}) \quad (X_2 e^{j\psi_2}) \quad (X_3 e^{j\psi_3}) \quad \cdots \quad (X_N e^{j\psi_N})]$. It is known that the inner product would reach the maximal magnitude when the two vectors are "parallel to each other" and the inner product's value is zero when the two vectors are "perpendicular to each other". Therefore, in order to maximize $|b_t|^2$, the wireless power excitations should be tailored to be "parallel to" S_{tn}, $n = 1, 2, 3, \ldots, N$. If the circuit network in Fig. 10 is a reciprocal network, $S_{tn} = S_{nt}$, $n = 1, 2, 3, \ldots, N$. Because S_{nt}, $n = 1, 2, 3, \ldots, N$, are readily available from (2), the wireless power excitations should be chosen to be "parallel to" the pilot signals detected in the first step. Specifically, $|b_t|^2$ would be maximized when

$$X_n e^{j\psi_n} = C(P_n)^* = C(A_n e^{j\alpha_n})^* = C A_n e^{-j\alpha_n}, \tag{4}$$

where C is a real-valued constant. After (2) is substituted into (4),

$$X_n e^{j\psi_n} = C(P_n)^* = C(a_t S_{nt})^* = C(a_t)^* (S_{nt})^*. \tag{5}$$

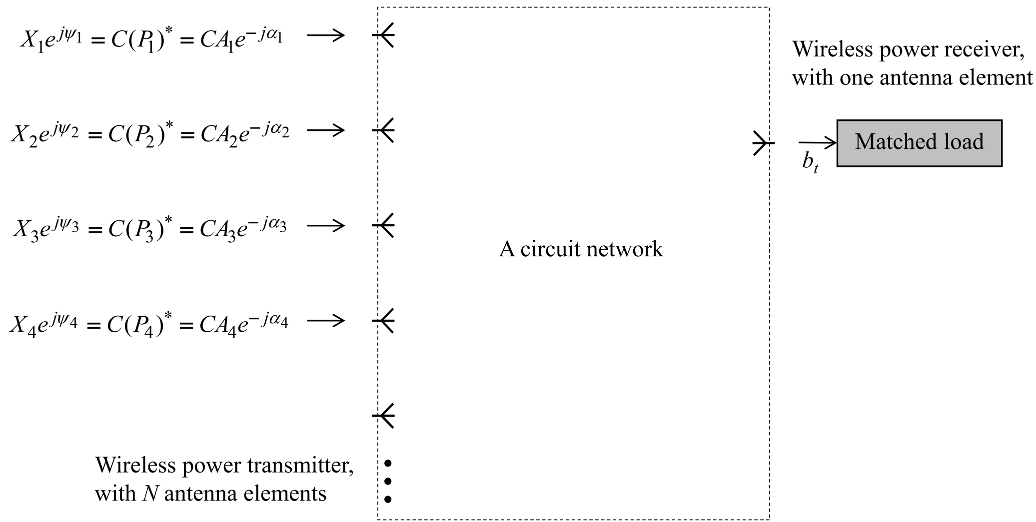


Fig. 12. Analysis of time-harmonic wireless power propagation.

With the excitations of (5), $|b_t|^2$, which is the power received by the wireless power receiver in the second step of retro-reflective beamforming, reaches the maximal value

$$|b_t|^2 = \left|\sum_{n=1}^{N} S_{tn}(X_n e^{j\psi_n})\right|^2 = \left|\sum_{n=1}^{N} S_{tn} C(a_t)^*(S_{nt})^*\right|^2 = C^2|a_t|^2\left(\sum_{n=1}^{N}|S_{tn}|^2\right)^2. \tag{6}$$

In addition, with the excitations of (5), the total power transmitted by the wireless power transmitter in the second step of retro-reflective beamforming is

$$\sum_{n=1}^{N}|X_n|^2 = C^2|a_t|^2\sum_{n=1}^{N}|S_{nt}|^2. \tag{7}$$

The ratio between (6) and (7) is the optimal power transmission efficiency

$$\sum_{n=1}^{N}|S_{nt}|^2 = |S_{1t}|^2 + |S_{2t}|^2 + \cdots + |S_{Nt}|^2. \tag{8}$$

Obviously, Eq. (4) is equivalent to

$$\begin{cases} X_n = CA_n \\ \psi_n = -\alpha_n \end{cases} \tag{9}$$

Eq. (9) indicates that the conjugation relationship between pilot signal reception and wireless power excitation ensures the optimal power transmission efficiency under the condition of channel reciprocity. When the wireless propagation channels involve multi-path (for instance, if certain obstacles exist between the wireless power transmitter and wireless power receiver), Eq. (9) always leads to the optimal power transmission efficiency as long as the multi-path channels are reciprocal. Eq. (9) resembles the mathematical expression of matched filter [33]. Whereas a matched filter intends to maximize the signal-to-noise ratio, the retro-reflective beamforming technique aims to maximize the power transmission efficiency. In the applications of wireless power transmission, C in (9) is much greater than 1 and its specific value is determined by the power budget of wireless power transmitter.

When the derivation above is extended from the frequency domain to the time domain, the time-reversal technique is arrived at. Suppose a waveform generator is attached to the wireless power receiver's antenna element in the first step of retro-reflective beamforming, and it generates a pilot signal with a time domain waveform that is not time-harmonic. As depicted in Fig. 13, the pilot signals in the time domain detected by the N antenna elements of wireless power transmitter are denoted as $p_1(t)$, $p_2(t)$, …, $p_N(t)$. According to the theory of Fourier transformation, each time domain pilot signal $p_n(t)$ can be characterized by its spectrum $P_n(\omega)$ as

$$p_n(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} P_n(\omega)e^{j\omega t}d\omega, \tag{10}$$

where $\omega = 2\pi f$ is the angular frequency. Denote $P_n(\omega) = A_n(\omega)e^{j\alpha_n(\omega)}$. In the second step of retro-reflective beamforming, suppose the wireless power excitation is prepared "one frequency by one frequency". Specifically, suppose the wireless power excitation to the nth antenna element of wireless power transmitter has amplitude $X_n(\omega)$ and phase $\psi_n(\omega)$ at angular frequency ω. Following (9), the wireless power excitation at ω is prepared as $X_n(\omega) = CA_n(\omega)$ and $\psi_n(\omega) = -\alpha_n(\omega)$. Then as shown in Fig. 14, the time domain wireless power excitation to the nth antenna element is

$$\begin{aligned} \frac{1}{2\pi}\int_{-\infty}^{+\infty} X_n(\omega)e^{j\psi_n(\omega)}e^{j\omega t}d\omega &= \frac{1}{2\pi}\int_{-\infty}^{+\infty} CA_n(\omega)e^{-j\alpha_n(\omega)}e^{j\omega t}d\omega \\ &= C\frac{1}{2\pi}\int_{-\infty}^{+\infty}[P_n(\omega)]^* e^{j\omega t}d\omega \\ &= Cp_n(-t) \end{aligned} \tag{11}$$

Comparison between Figs. 13 and 14 indicates that the wireless power excitation to the nth antenna element in Fig. 14 is the time-reversed version of the pilot signal detected by the nth antenna element in Fig. 13. Thus, the retro-reflective beamforming technique is essentially equivalent to the time-reversal technique [34,35]. The time-reversal technique can be appreciated by the "rewind" button of a movie player. If the propagation of pilot signal in the first step of retro-reflective beamforming is considered as a movie, the propagation of wireless power in the second step of retro-reflective beamforming appears like the rewound movie. Specifically, the pilot signal propagation diverges in the space whereas the wireless power propagation converges onto the wireless power receiver, from which the pilot signal is broadcasted. It is worthwhile noting that the retro-reflective beamforming scheme or time-reversal technique is not limited to optical wave or electromagnetic wave; for instance, an acoustic time-reversal sink is researched in [36].

3. Three applications of microwave power transmission based on retro-reflective beamforming

As elucidated in Section 1.1, several practical restrictions make it a challenging task to deliver wireless power via microwave carrier over long distance. Nevertheless, it is possible that commercial products of microwave power transmission would emerge in three applications in

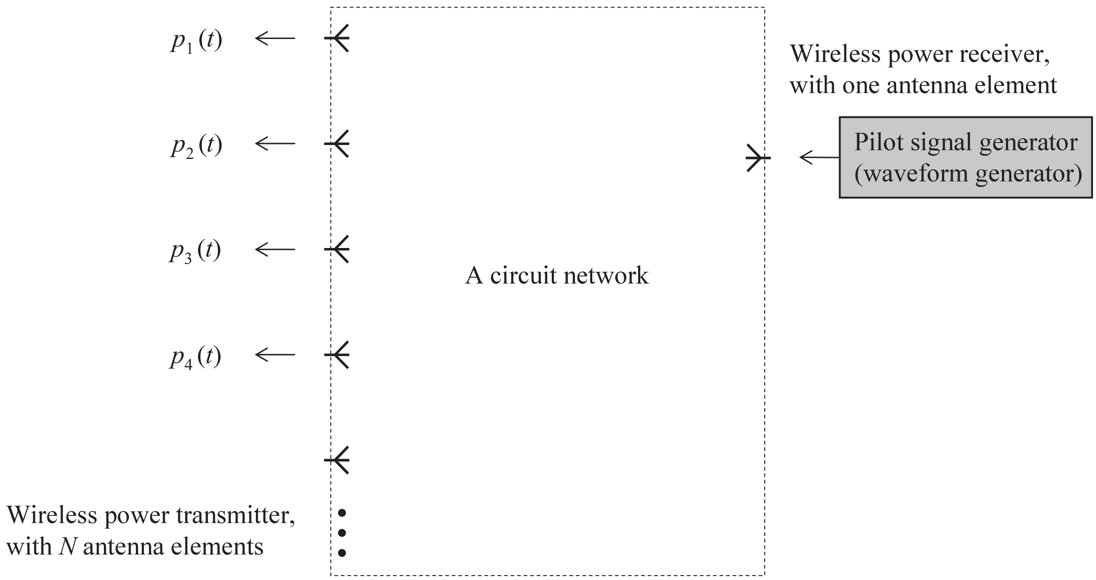


Fig. 13. Pilot signal propagation in the time domain.

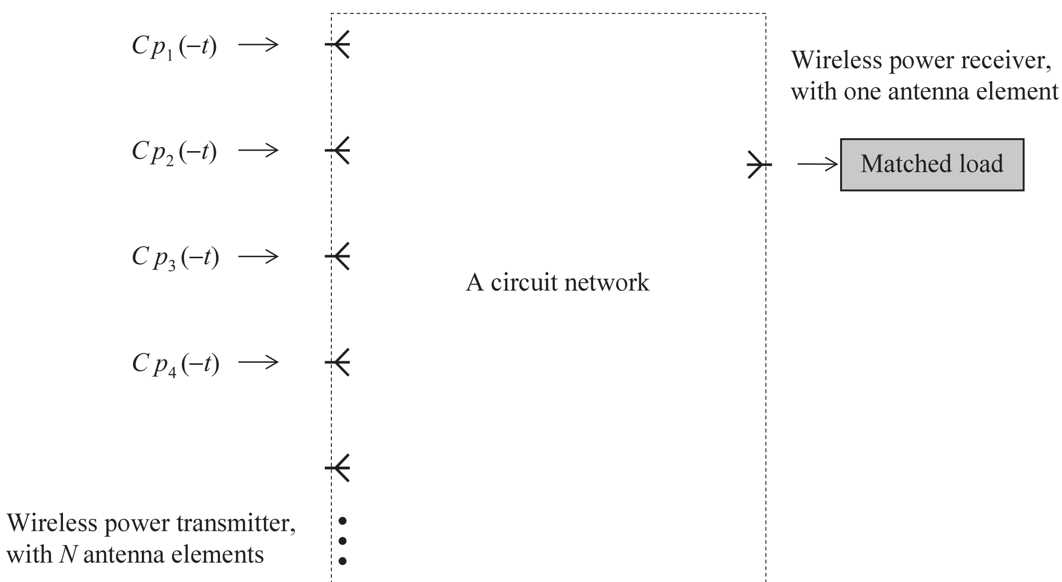


Fig. 14. Wireless power propagation in the time domain.

the near future, which are discussed in the following three subsections respectively.

3.1. Microwave power transmission in Internet of Things applications

Internet of Things is one of the fastest-growing markets in the world [37]. The development of Internet of Things intends to incorporate physical objects into the Internet. As foreseen by the US National Intelligence Council, by 2025 all kinds of everyday things will become “nodes” on the Internet, such as food packages, furniture, paper documents, and certain personnel [38]. The impact of Internet of Things on industry, business, and individual people is expected to be tremendous and profound.

“Tag” is a crucial element of the Internet of Things. A tag attached to an object keeps track of the object’s status (model number and manufacturing date, for instances). Once the tag is read by “tag readers” ubiquitously installed over the society’s infrastructures (such as factories, warehouses, and supermarkets), the object’s entity is converted to the digital format; furthermore since all the tag readers can be connected to the Internet, the object can be traced by other members of the Internet. Although conventional tags comprised of optical barcode have been employed for decades, the Internet of Things is based upon another type of tag: Radio-frequency identification (RFID) tags. RFID tags can be considered “electronic barcodes”. Compared with optical barcodes, RFID tags can be read from much longer distance, and in addition, reading RFID tags does not require line-of-sight. These distinctive advantages make RFID tags a better candidate for Internet of Things. Today, RFID tags are always integrated with various sensors (such as temperature sensors and humidity sensors), resulting in RFID sensor tags.

Ideally, RFID tags should be small, light, low-cost, and readable from long distances (10 m or longer, for instance). In addition, RFID tags are often required to accommodate various sensors and be able to conduct certain complex operations like encryption. It is highly challenging for an RFID tag to satisfy all the above-mentioned requirements. Consequently, there are two categories of RFID tags.

Table 2
Comparison among optical barcode, passive RFID tags, and active RFID tags.

	Optical barcode 	Passive RFID tag 	Active RFID tag 
Reading distance	Less than 1 meter	A few meters	Up to hundreds of meters
Line-of-sight?	Yes	No	No
Functionalities	Simple	Simple	Sophisticated
Cost	Low	Low	High
Size and weight	Low	Low	High
Onboard battery?	No	No	Yes

- Passive RFID tags do not have onboard batteries. They are small, light, and low-cost. However, their reading range is limited to a few meters typically and they are unable to carry out complex jobs. Passive tags are suitable for applications with strict demands regarding minimization of size, weight, and cost.
- Active RFID tags have onboard batteries. Their reading range can reach hundreds of meters and they can accommodate sophisticated functionalities. Nevertheless, the onboard battery increases the tags' size, weight, and cost. Also, the tags' lifetime is restricted by the battery's capacity. Active tags are applicable when size, weight, cost, and lifetime are not the end users' top concerns.

Table 2 presents metrics to compare optical barcode, passive RFID tag, and active RFID tag among one another.

With a "wireless charging module" incorporated, a new type of RFID tag would exhibit the advantages of passive tags and active tags simultaneously, and thus would satisfy the requirements of Internet of Things better. The new type of RFID tag has a small rechargeable battery onboard. While the RFID tag communicates information to an RFID reader, the RFID reader transmits wireless power to charge the tag's battery. Since the proposed tags are able to acquire power from the reader on demand, a small onboard battery suffices (many commercially-available thin-film and solid-state batteries are good candidates [39,40]). As a result, the new type of tag is almost as small, light, and low-cost as passive RFID tags. Because of the onboard battery, the tags with "wireless charging modules" also have the advantages of active RFID tags such as long reading range and sophisticated functionalities.

Wireless charging based on microwave power transmission is especially suitable for RFID tags due to the following three reasons. First, the number of RFID tags is huge in practice. Typically, an individual person has little difficulty charging his/her cell phone using a wired adapter when the cell phone's battery is near depletion. However, if one RFID tag is attached to every book on a bookshelf, it would be almost impossible for him/her to keep track of the tags and charge them in a timely manner. Wireless charging is undoubtedly an excellent resolution to manage the rechargeable battery of a large number of devices. Second, mobility is one of the most outstanding merits of RFID tags. The microwave power transmission technology is capable of providing wireless power to RFID tags remotely without sacrificing their mobility, and therefore is desirable in practice. Third, RFID tags are not power hungry and do not require powerful wireless power transmitters. If the microwave power transmission technology offers 1% of power transmission efficiency in an indoor environment and if an RFID tag is in need of 10 mW of power, the power transmitted by a wireless power transmitter is 1 mW ÷ 1% = 1 Watt. Obviously, all the practical concerns pertinent to microwave power transmission, such as potential biological hazards, are negligible when the transmitted power is as low as 1 Watt. In summary, although every mobile electronic device may benefit from microwave power transmission in principle, the feasibility of applying microwave power transmission technology to the mobile electronic devices of Internet of Things appears especially high.

The retro-reflective beamforming technique has the potential to enable efficient microwave power transmission to RFID tags, as illustrated in Fig. 15. Suppose there are thousands of containers in a warehouse and an RFID tag is attached to each container. An RFID reader system is installed in the warehouse, consisting of a base station and multiple panels. The panels are mounted over the ceiling or walls of the warehouse. Each panel includes an array of planar antennas. The multiple panels work collaboratively to communicate with the tags, localize the tags, and supply wireless power to the tags. Specifically, the two-step scheme of retro-reflective beamforming illustrated in Fig. 9 can be applied to accomplish the third goal above (i.e., charging the tags wirelessly). In the first step, one or more than one tag(s) broadcast pilot signals. In the second step, the panels jointly construct microwave power beam(s) onto the target tag(s) in response to the pilot signals. A panel transmits power only if it has line-of-sight interaction with the target tag; if the line-of-sight path is blocked by any obstacle, the panel is deactivated such that the obstacle, which might be a human being, is not illuminated by power beams directly [41–43].

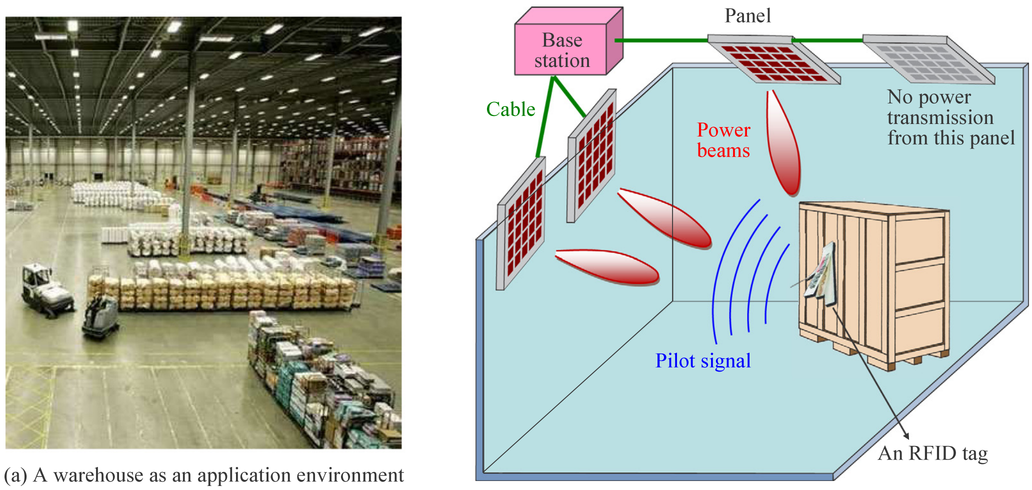
3.2. Microwave power transmission in space solar power applications

The concept of space solar power satellites (SSPS) was proposed in 1968 [44]. It aims to harvest solar power by satellites over the earth's geostationary orbit and then deliver the harvested power to the earth wirelessly. If successfully implemented, SSPS would supply power on the order of Giga-Watts to the earth steadily and continuously, and thus is anticipated to be a resolution to the global energy crisis in front of the mankind. Compared with solar power harvesting on the earth, solar power harvesting in the outer space offers tremendous benefits. Solar power is not available at night on the earth. Consequently, solar power harvesting on the earth must be coupled with either another energy source or an energy storage system in practice. When the location of a space solar power satellite is selected appropriately, in contrast, the satellite is almost always under the sunshine. Moreover, solar power harvesting in the outer space is not impacted by the earth's atmospheric conditions whereas the performance of solar power harvesting on the earth heavily depends on the weather conditions. In other words, space-based solar power harvesting does not suffer from the shortcomings of discontinuity or instability as most of the renewable energy sources do.

As an extremely complex engineering system, the feasibility of SSPS is still under assessment/discussion to date. The readers are referred to [45] for an overview of the engineering/technical topics covered by SSPS.

Wireless power transmission is a critical element of the SSPS concept. As depicted in Fig. 16, the solar power harvested by a satellite must be delivered to the earth wirelessly over a distance of about 36,000 km. During the past few decades, enormous research efforts have been reported on the wireless power transmission from a space solar power satellite to the earth. Ref. [46] (which was published in 2013) provides a comprehensive description of the research endeavors before 2013. The recent and ongoing developments pertinent to wireless power transmission in SSPS were reviewed in [18,47,48]. The microwave frequency range between 1 GHz and 10 GHz is found suitable for carrying the wireless power in SSPS applications, after a large number of practical factors are taken into account [46,49]. Two ISM frequency bands, which are around 2.45 GHz and 5.8 GHz respectively, are believed to be particularly excellent candidates.

In order to transmit microwave power efficiently over 36,000 km, the antenna panel over the geostationary satellite must have a large physical aperture (on the order of 1 $(km)^2$, to be specific). With respect to the earth, the physical position and attitude/orientation of the antenna panel are not completely fixed. Rather, the antenna panel's physical position and attitude/orientation are maintained around the



(a) A warehouse as an application environment

(b) Technical schematic

Fig. 15. Illustration of retro-reflective beamforming technique for microwave power transmission to RFID tags.

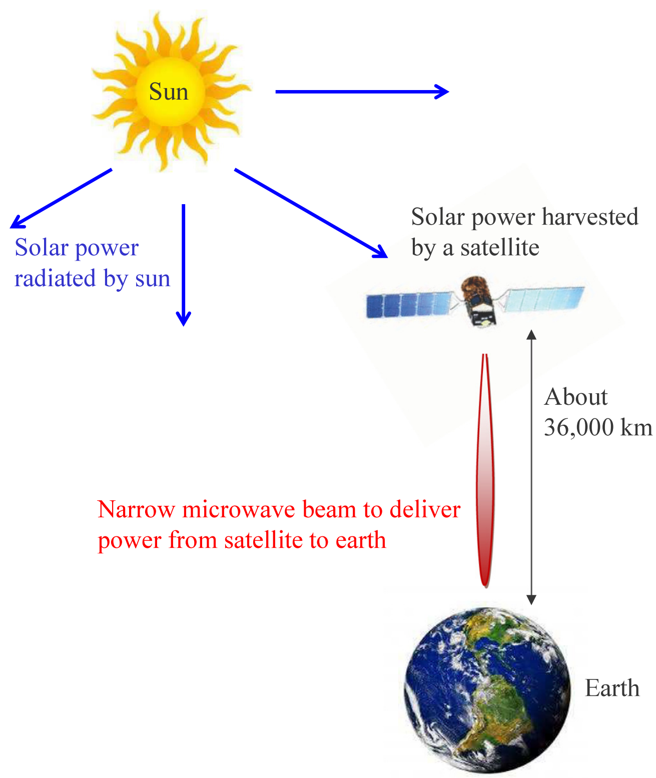


Fig. 16. Illustration of microwave power transmission from satellite to earth in SSPS applications.

desired status by a sophisticated mechanical control system over the satellite. In order to mitigate power loss and possible hazards, it is imperative to ensure that most of the wireless power transmitted by the satellite is collected by a designated ground station on the earth when the antenna panel's physical condition is under constant change. Therefore, the wireless power transmission from a geostationary satellite to the earth must meet two technical requirements. First, a narrow beam needs to be generated by the antenna panel as the carrier of wireless power. Second, the beam needs to be steered toward the designated ground station precisely in response to the slight change of antenna panel's position or attitude.

Indeed, the Internet of Things applications (which are discussed in Section 3.1) impose two similar requirements for wireless power transmission. Specifically in Internet of Things, a wireless power transmitter is desired to deliver wireless power to a mobile wireless power receiver (e.g., an RFID tag) through a narrow beam, and the narrow beam must be reconfigured to follow the location of the mobile wireless power receiver in real time. Now that the retro-reflective beamforming scheme illustrated in Fig. 9 has the potential to address the two requirements imposed by Internet of Things, it should be applicable to the SSPS applications without fundamental alterations.

The ideal scenario of wireless power transmission based on retro-reflective beamforming in SSPS applications is illustrated in Fig. 17(a). The antenna panel over a space solar power satellite includes a planar retro-reflective antenna array. A pilot signal is broadcasted from a ground station on the earth. After the pilot signal is detected and analyzed by the retro-reflective antenna array, a microwave power beam is constructed by the retro-reflective antenna array toward the ground station, from which the pilot signal is originated. The retro-reflective antenna array resides in the x-z plane, with its antenna elements deployed along x direction and z direction. The geometrical center of the antenna array is designated as the spatial origin. The ground station is centered at $(x = 0, y = d, z = 0)$ where $d = 36{,}000$ km is the distance between the geostationary satellite and the earth. The ground station is assumed to have a square aperture parallel to the x-z plane in Fig. 17. In practice, the antenna array's position and attitude are not fixed with respect to the ground station. Specifically, the antenna array's position and attitude are maintained around the desired status by a mechanical control system over the space solar power satellite. Fig. 17(b) illustrates the practical scenario with the antenna array's attitude deviating from the ideal status. Guided by a pilot signal broadcasted from the ground station in Fig. 17(b), the retro-reflective antenna array generates a narrow microwave power beam toward the ground station.

3.3. Microwave power transmission in fully-enclosed space

A microwave oven is fully enclosed by conducting walls. The conducting walls prevent microwave power from leaking out of the oven. The electrical blockage due to conducting walls not only increases the efficiency of heating inside the oven but also avoids possible hazardous impacts on the exterior region. The practical application of this technical concept can be extended from heating to wireless charging [50]. As proposed in Fig. 18, an oven-like box fully enclosed by conducting walls is fabricated for the purpose of wireless charging:

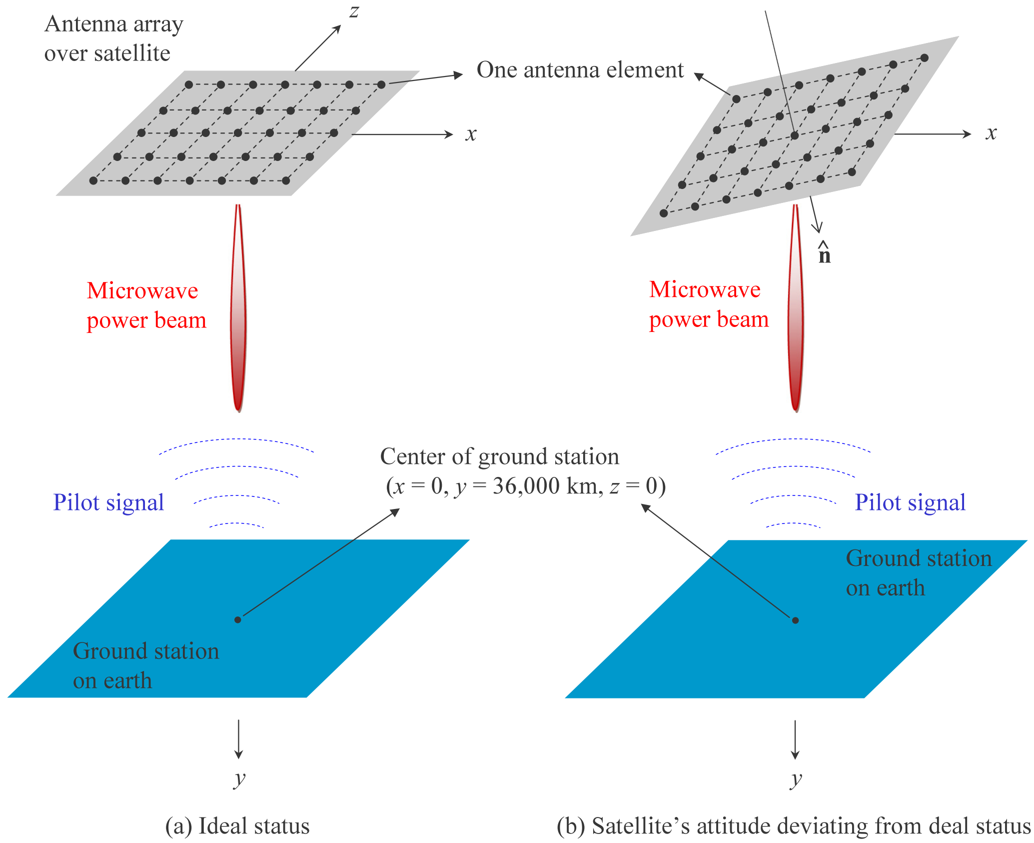


Fig. 17. Two scenarios of wireless power transmission from a geostationary satellite to the earth based on retro-reflective beamforming technique (not to scale).

When multiple electronic devices are placed inside the box, their rechargeable batteries get charged without any wiring. The wireless charging box in Fig. 18 offers higher charging capacity than the commercially-available wireless charging pads (which are shown in Fig. 2). Since the wireless charging pads rely on non-radiative magnetic field, electronic devices must be physically placed on a pad in order to be charged efficiently. In other words, a wireless charging pad only takes advantage of a two-dimensional surface. In contrast, the wireless charging box in Fig. 18 employs a three-dimensional region, and thus would enable more electronic devices to be charged simultaneously.

As a drawback of the scheme in Fig. 18, the electronic devices are not mobile or portable when they are charged in the wireless charging box. Rather, the electronic devices must be collected and placed in the wireless charging box manually before they could be charged wirelessly. Moreover, all the functionalities of the electronic devices must be paused while the wireless charging is in process. Although not being able to preserve the mobility or portability of electronic devices, the wireless charging box in Fig. 18 offers three distinctive benefits. First, high wireless power transmission efficiency might be accomplished in the wireless charging box. Second, wireless power transmission in the wireless charging box generates no hazards in the exterior region. Third, it is possible for a large number of electronic devices to be charged simultaneously without any wiring. The wireless charging box depicted in Fig. 18 would be valuable for practical applications where a large number of electronic devices are necessities but are not in need constantly. Below is one example. Many tourism resorts utilize audio tour guides to assist the visitors. A typical audio tour guide device is a wireless device with rechargeable battery. If the audio tour guide devices are collected by a museum staff and placed in the wireless charging box after the museum is closed, they would be charged at night and be ready for the next day.

When a set of permanent positions are prescribed for wireless charging (by the racks and by the electronic device holders in Fig. 18, for instance), it seems unnecessary to reconfigure the wireless power distribution in a wireless charging box. Nevertheless, it is always desirable to adjust the pattern of wireless power in real time. For instance, if Device A's rechargeable battery is almost full while Device B's rechargeable battery is nearly empty, illuminating Device B with stronger wireless power than Device A would improve the system's efficiency. Ideally, the wireless charging box ought to be "smart:" The wireless charging box ought to communicate with the electronic devices periodically and then reconfigure the wireless power distribution in the box according to the devices' need.

In addition to microwave ovens, plenty of practical environments are fully enclosed or almost fully enclosed by conducting walls, such as spacecrafts [51], submarines, engine compartments [52,53], and some greenhouses [54]. Wireless power transmission has potential applications in these fully-enclosed environments. For instance, if a wireless sensor attached to a rotary shaft in an engine compartment has access to wireless power, it would be unnecessary to stop the engine for the sake of charging the sensor. As another example, wireless power transmission in fully-enclosed space has enabled powering devices implanted in animal bodies wirelessly in medical experiments [55–57]. The technology proposed in Fig. 18 may be applicable to equip the above-mentioned practical environments with a wireless charging module. Apparently, electronic devices are stationary with fixed locations in a wireless charging box, whereas electronic devices' mobility or portability should not be sacrificed when they acquire wireless power in practical environments like spacecrafts or submarines. Thus, it seems that wireless power transmission would not reach the optimal performance without reconfigurability in fully-enclosed space (such as a wireless charging box, a space station, etc.).

Although the technical concept of Fig. 18 resembles wireless charging pads, the underlying technology of wireless charging pads cannot be extended to Fig. 18 straightforwardly. Because wireless charging pads intend to minimize radiative fields, their operating frequency

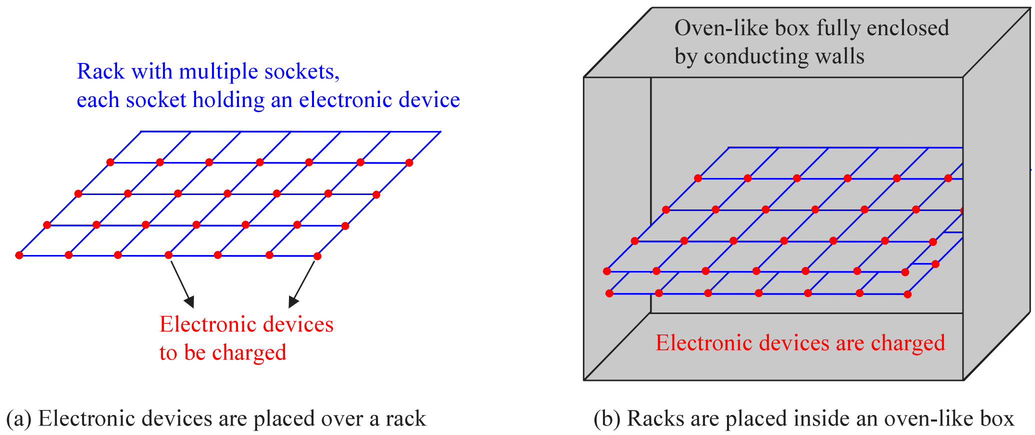


Fig. 18. Depiction of wireless charging box.

is typically below 1 MHz [58]. When the frequency is as low as 1 MHz, the fully-enclosed box in Fig. 18 behaves as a large capacitive load to the wireless power transmitter. In order to achieve conjugate matching, the wireless power transmitter must incorporate a large inductance to neutralize the capacitive load [12,13], which leads to a range of technical complications. Thus, it seems more optimal to upgrade the operating frequency to be close to the natural resonant frequencies of the fully-enclosed box. When the physical dimension of the fully-enclosed box is on the order of 1 m, the resonant frequencies are higher than 100 MHz. Therefore, microwave power transmission based on retro-reflective beamforming technique may be applied to achieve efficient and reconfigurable wireless power transmission in fully-enclosed space.

Whereas the retro-reflective beamforming scheme in Section 2 is applicable in fully-enclosed space, it may lead to poor performance of wireless power transmission because the cavity walls create rich multi-path in Fig. 18. As an alternative, a retro-reflective beamforming technique based on parasitic array is proposed in Fig. 19 for wireless power transmission in fully-enclosed space. A wireless power transmitter includes M antenna elements. One of the M elements is the driver element. The other (M - 1) elements, termed as “parasitic elements”, are terminated by tunable purely-reactive loads. Each wireless power receiver includes one antenna element. The wireless power receivers acquire wireless power from the wireless power transmitter via two steps. In the first step (Fig. 19(a)), a low-power time-harmonic pilot signal is broadcasted by a wireless power receiver. A power detector is attached to the driver element of wireless power transmitter. The loads of parasitic elements are adjusted until the power detector’s output is maximal. The reactance values of the (M - 1) loads corresponding to the maximal power detector’s output are recorded as $jX_1, jX_2, \dots, jX_{M-1}$. In the second step (Fig. 19(b)), the driver element is excited by a time-harmonic power source with the same frequency as the pilot signal, and the wireless power receiver is terminated by a matched load. The (M - 1) loads’ values are fixed as $jX_1, jX_2, \dots, jX_{M-1}$. (It is worth noting that “X” denotes “reactance” in this section while “X” stands for “excitation amplitude” in Section 2.)

When a parasitic array is employed as a transmitting antenna, the driver element is the only active element, that is, the driver element is excited by a power source. After the source’s power is radiated by the driver element, certain portion of the power is coupled to the parasitic elements. The coupled power is re-radiated, as the parasitic elements are terminated by purely-reactive loads. The total electromagnetic field radiated by the parasitic array is the sum of direct radiation from the driver element and re-radiation from the parasitic elements. If the reactive loads are tunable, the re-radiation’s phase would be altered and the total field would be reconfigurable [59,60].

In a parasitic array, the contribution of a certain parasitic element to the total electromagnetic field depends on how much power it couples from the driver element. In other words, if the coupling between the driver element and a certain parasitic element is weak, the parasitic element’s role is minimal. As far as wireless power transmission in fully-enclosed space is concerned, the parasitic array appears to be an excellent candidate. Since radiation is blocked by conducting walls in fully-enclosed space, it is possible for the coupling between the driver element and parasitic elements to be very strong. Consequently, a parasitic element could play an important role even when it is far away from the driver element in space.

Assume that the fully-enclosed space is lossless and its conducting walls are lossless too. At the same time, assume that the (M - 1) parasitic ports’ terminations in Fig. 19(b) are lossless as well. The power delivered to the wireless power receiver would be maximized when the outgoing/reflected power at the driver port is minimized. If the regular retro-reflective beamforming scheme illustrated by Fig. 10 is applied in fully-enclosed space, however, the power delivered to the wireless power receiver would be maximized when the total outgoing power at the wireless power transmitter’s ports is minimized. As a result, it seems easier to achieve higher power transmission efficiency with the parasitic antenna array of Fig. 19.

As a relatively new research topic, wireless power transmission in fully-enclosed space has not been explored comprehensively or thoroughly [61,62]. Therefore, the optimal scheme of wireless power transmission in fully-enclosed space is subject to further investigations.

4. Conclusion

The retro-reflective beamforming technique has excellent potential to accomplish efficient wireless power transmission to non-stationary wireless power receivers. The basic principles and potential applications of wireless power transmission based on retro-reflective beamforming technique are reviewed in this paper.

Declaration of competing interest

Mingyu Lu is an editorial board member for Space Solar Power and Wireless Transmission and was not involved in the editorial review or the decision to publish this article. All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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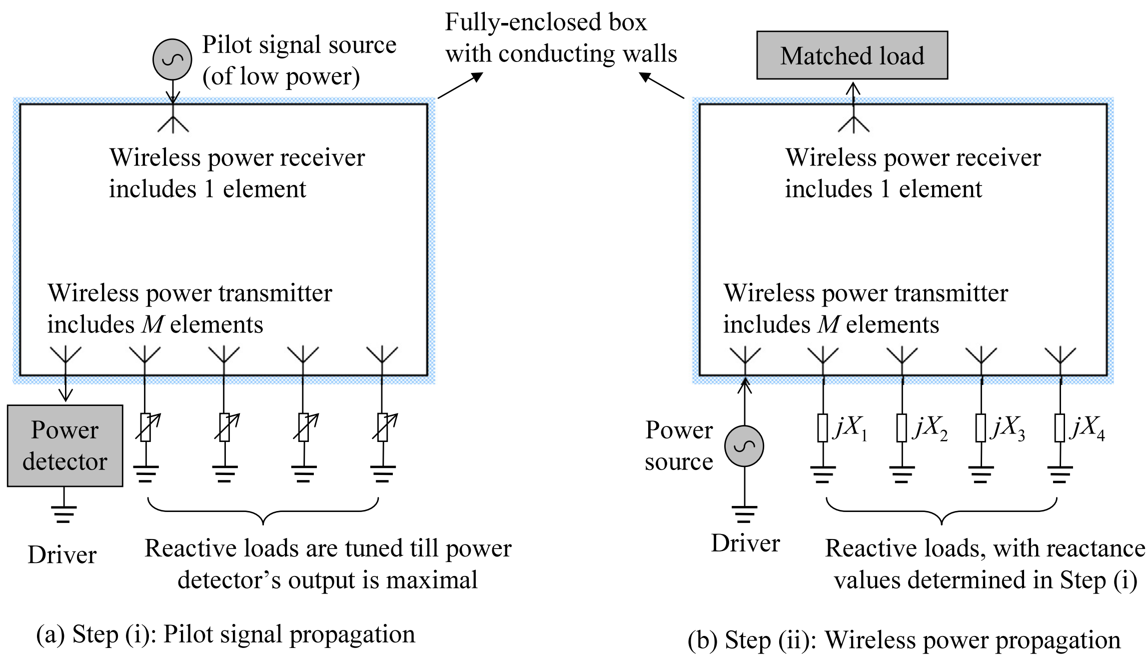

Fig. 19. Illustration of retro-reflective beamforming technique based on parasitic array for wireless power transmission in fully-enclosed space.

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