Toward 1G Mobile Power Networks

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Thanks to the quality of the technology and the existence of international standards, today's wireless communication networks (based on RF radiation) underpin contemporary societies' global functioning. The pursuit of higher spectral efficiency has been going on for approximately four decades, with fifth-generation (5G) technologies expected in 2020. The development of 5G and beyond will see the emergence of trillions of low-power autonomous wireless devices for applications such as ubiquitous sensing through an Internet of Things (IoT).

The Faces of Wireless

Wireless, however, is more than just communications. For very short ranges, wireless power charging via inductive power transfer is a reality with available products and standards (including those by the Wireless Power Consortium, the Power Matters Alliance,

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and the Alliance for Wireless Power, such as Rezence). On the other hand, wireless power via RF (as in wireless communication) could be used for longer ranges via two different methodologies: wireless energy harvesting (WEH) and wireless power transfer/transmission (WPT). While WEH assumes that RF transmitters are designed exclusively for communication purposes (the ambient signals of which can be harvested), WPT relies on dedicated sources designed exclusively for wireless power delivery. Wireless power via RF has long been regarded as a possibility for energizing low-power devices, but only recently has this possibility been recognized as feasible. According to [1], at a fixed computing load, the amount of required energy falls by a factor of two every year-and-a-half due to the evolution of electrical efficiency in computer technology. This explains why relying on wireless power to perform meaningful computation tasks at reasonable distances became feasible only over the last few years and so now justifies the recent interest in wireless power.

The emergence of RF identification (RFID) technology over the last decade is the first sign of this interest in far-field wireless power. RFID tags use the RF signal of an RFID reader (transmitter) for power and communication. They rely on backscattering modulation to reflect and modulate the incoming RF signal. The interest in RFID is motivated by numerous industrial applications and has led to the development of a physical layer, standards, and a body of research focused on the design of novel tags, protocols, and readers.

Recent work proposes that, in the future, wireless networking go beyond conventional communication-centric transmission. In the same way that wireless (via RF) has disrupted mobile communications for the last 40 years, wireless (via RF) will now disrupt the delivery of mobile power. However, current wireless networks are designed for communication purposes only. While mobile communication has become a relatively mature technology as it evolves toward 5G, the development of mobile power is in its infancy and has yet to reach even its first generation (1G): not a single standard exists for mobile power and far-field WPT.

Despite being subject to regulations regarding exposure to electromagnetic fields (as is wireless communication), wireless power brings numerous new opportunities. It enables proactive and controllable energy replenishment so that devices no longer depend on centralized power sources, which allows for genuine mobility: no wires, no contacts, and no (or, at least, reduced-size) batteries, leading to lighter, more compact devices. It is also an ecologically sound solution, eliminating the production, maintenance, and disposal of trillions of batteries, in addition to prolonging device lifetimes and creating a long-term, predictable, and reliable energy supply (as opposed to ambient energy-harvesting technologies such as solar, thermal, and vibration). This is particularly important for future networks with ubiquitous and autonomous low-power and energy-limited devices, device-to-device communications, and the IoT with its massive connectivity.

Radio waves simultaneously carry both energy and information. Traditionally, energy and information have been treated separately and have evolved as two independent fields of work in academia and industry, i.e., wireless power and wireless communication. This separation has several consequences:

- Current wireless networks pump RF energy into the free space (for communication purposes) but do not make use of it for energizing devices.
- Providing ubiquitous mobile power would require deploying a separate network of dedicated energy transmitters.

Imagine, instead, a wireless network in which information and energy flow together through the wireless medium. Wireless communication (or wireless information transfer) and WPT would refer to two extreme strategies targeting, respectively, communications only and power only. A unified wireless information and power transfer (WIPT) design could evolve unobtrusively in between those two extremes, making the best use of the RF spectrum/radiations and of network infrastructure to communicate, energize, and, hence, outperform traditional systems that rely on a separation of communications and power.

This article reviews some promising recent approaches that could move this vision closer to reality. Most work published within the microwave and communication/signal processing communities emphasizes either RF, circuit, and antenna solutions for WPT on the one hand or communications, signal, and system designs for WPT on the other. This review article, in contrast, uniquely bridges RF, signal, and system designs to bring those areas closer to one another and so provide a better understanding of the fundamental building blocks for an efficient WPT network architecture. We start by reviewing the engineering requirements and design challenges involved in making mobile power a reality. We then summarize the state of the art in a wide range of areas spanning sensors and devices, RF design for wireless power, and wireless communications. We identify the limitations of each and make critical observations, before providing a fresh look at some promising avenues for signal and system designs in WPT.

Engineering Requirements and Design Challenges for the Envisioned Network

We define the following as the engineering requirements and main design challenges for the envisioned network (not in order of priority):

- *range*: deliver wireless power at distances of 5–100 m for indoor/outdoor charging of low-power devices
- *efficiency*: boost end-to-end power transfer efficiency (up to a fraction of percent/a few percent)
- *non-line of sight (NLoS):* support LoS and NLoS to widen the practical applications of this network
- *mobility support*: support mobile receivers, at least for those at pedestrian speeds
- *ubiquitous accessibility*: support ubiquitous power accessibility within the network coverage area
- *seamless integration of wireless communication and wireless power*: interoperate wireless communication and wireless power via a unified WIPT
- *safety and health*: resolve the safety and health issues of RF systems and comply with regulations
- *energy consumption:* limit the energy consumption of energy-constrained RF-powered devices.

Power Requirements and Consumption of Sensors and Devices

The integrated circuit (IC) industry is moving from a traditional computing power paradigm toward a power-efficiency (lowest joule per operation) paradigm. These ultralow-power (ULP) electronics have opened the door to numerous applications, in sensor networks and the IoT, that do not require nanometer technology using billions of gates. Sensor nodes commonly demand power for the sensor itself, the data processing circuitry, and the wireless data link (e.g., a few bits per second for temperature sensors to a few kilobits per second for electrocardiogram or blood pressure monitoring). The first two functions commonly require less power.

While complementary–metal-oxide-semiconductor (CMOS) technology scaling has conventionally provided benefits for digital logic systems' size and power consumption, analog RF components (needed for the data link) have not seen similar power scaling. As examples, in [2], a CMOS image sensor consumes only 14.25 μW, while, in [3], low-power microphones consume 17 μW and an analog-to-digital converter digitizing the microphone output consumes 33 μW. Popular protocols for sensor networks include Zigbee and low-power Bluetooth, whose commercial off-the-shelf transmitters consume 35 mW [4]. Wi-Fi is, in fact, more power-hungry than protocols such as Zigbee and Bluetooth. Despite progress in the Wi-Fi industry to design chip sets for IoT applications by reducing power consumption in the standby mode to 20 μW, for example, active Wi-Fi transmission still consumes around 600 mW [5], [6].

Over recent years, there have been significant improvements in integrated ULP system-on-chip and duty-cycled radio, whose power consumption is now on the order of 10–100 μW using custom protocols supporting 10–200 kb/s [7]–[10]. The use of passive Wi-Fi is also an alternative for Standard 802.11b transmission over distances of 10–30 m (LoS and through walls), while consuming only 10 and 60 μW for 1 and 11 Mb/s transmissions, respectively (three to four orders of magnitude lower than existing Wi-Fi chip sets) [11]. Note that 10–100 μW is sufficient to power modern wireless sensors and low-power devices.

WPT RF Design

Since Tesla's early attempts at WPT in 1899 and continuing experiments from 1960 to 2000, WPT targeted long-distance and high-power transmissions, with applications such as solar power stations/satellites and wirelessly powered aircraft [12]. More recently, significant interest has focused on WPT and WEH for relatively low-power (e.g., from microwatts to a few watts) delivery over moderate distances (e.g., a few meters to hundreds of meters) [13], [14]. This is due to the fast-growing need to build reliable and convenient wireless power systems to remotely charge various low- to medium-power devices, such as RFID tags, wireless sensors, and consumer electronics [15], [16]. The interest in far-field wireless power has spurred the creation of initiatives such as COST IC1301 [17] and a small number of start-ups in recent years.

Figure 1 shows a generic wireless power delivery system consisting of an RF transmitter and an energy

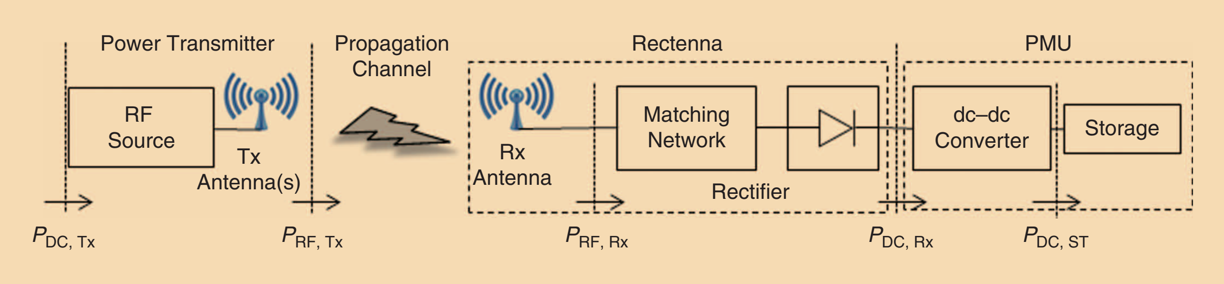

Figure 1. *A block diagram of a conventional far-field WPT architecture. TX: transmit; Rx: receive.*

harvester formed by an antenna combined with a rectifier (rectenna) and a power-management unit (PMU). Because most electronics require a dc power source, a rectifier is required to convert RF to dc. The recovered dc power then either supplies a low-power device directly or is stored in a battery or a supercapacitor for high-power, low-duty-cycle operations. The recovered dc power can also be managed by a dc-to-dc converter before being stored. Referring to Figure 1, the end-to-end power transfer efficiency e can be expressed as

$$e = \frac{\mathrm{P_{DC,ST}}}{\mathrm{P_{DC,Tx}}} = \underbrace{\frac{\mathrm{P_{RF,Tx}}}{\mathrm{P_{DC,Tx}}}}_{e_1} \underbrace{\frac{\mathrm{P_{RF,Rx}}}{\mathrm{P_{RF,Tx}}}}_{e_2} \underbrace{\frac{\mathrm{P_{DC,Rx}}}{\mathrm{P_{RF,Rx}}}}_{e_3} \underbrace{\frac{\mathrm{P_{DC,ST}}}{\mathrm{P_{DC,Rx}}}}_{e_4}. \qquad (1)$$

For WEH, the transmitter in Figure 1 is an RF communication transmitter, not controllable and not optimized for power delivery purposes. Given a typical power density of between 10^{-3} and 10^{-1} μW/cm^2 (as observed both indoors and outdoors at distances of 25–100 m from a GSM900 base station), WEH is considered insufficient for powering devices that are a few centimeters squared in size, requiring 10–100 μW [15]. For WPT, the power transmitter in Figure 1 can be fully optimized. Therefore, WPT offers more control of the design and room for enhancement of e. We briefly review the techniques used to enhance e_1, e_2, e_3, and e_4.

DC-to-RF Conversion Efficiency

Maximizing dc-to-RF conversion efficiency e_1 can leverage the rich literature on power amplifier design and rely on transmit signals with constrained peak-to-average power ratio (PAPR).

RF-to-RF Conversion Efficiency

RF-to-RF conversion efficiency e_2 is a bottleneck and requires highly directional transmission. Common approaches in the RF literature rely on real-time reconfiguration of time-modulated arrays based on localization of the power receivers [19], phased arrays [20], or retrodirective arrays [21]. New regulations on equivalent isotropically radiated power (EIRP) are also likely needed for WPT. Efforts to address EIRP in the 5.8-GHz band in the far-field region have already been performed [22].

RF-to-DC Conversion Efficiency

Maximizing RF-to-dc conversion efficiency e_3 requires designing efficient rectennas. A rectenna harvests electromagnetic energy and then rectifies and filters it using a low-pass filter. Its analysis is challenging due to its nonlinearity, which, in turn, renders its implementation difficult and subject to several losses due to threshold and reverse-breakdown voltage, device parasitics, impedance matching, and unwanted harmonics generation [23]–[25].

In WPT, the rectenna can be optimized for the specific operating frequencies and input power level. This is more challenging in WEH because the rectenna is designed for a broad range of input power densities (ranging from a few nanowatts per centimeter squared to a few microwatts per centimeter squared) and spectra [e.g., TV, Wi-Fi, and second/third/fourth generation (4G)] [18]. To address the large aggregate frequency spectrum of ambient RF signals, multiband [26]–[29] and broadband [30]–[32] rectifier designs have been proposed.

In the case of multiband designs, e_3 may be maximized over a number of narrow-band frequency regions; in the case of broadband (ultrawide-band) designs, however, a much larger frequency band may be covered, but this involves sacrifices in terms of the obtained maximum efficiency. Various rectifier technologies exist, including the popular Schottky diodes [13], [33], CMOS [34], active rectification [35], spin diodes [36], and backward tunnel diodes [37].

Assuming that $\mathrm{P_{RF,Tx}} = 1$ W, 5-dBi transmit/receive antenna gain, and a continuous wave (CW) at 915 MHz, the e_3 of state-of-the-art rectifiers is approximately 50% at 1 m (transmit-receive range), 25% at 10 m, and 5% at 30 m [36]. This severely limits the range of WPT. Moreover, with current rectifier technologies, e_3 drops from 80% at 10 mW (input power) to 40% at 100 μW, 20% at 10 μW, and 2% at 1 μW [25], [36], due to the diode not being easily turned on at low input power. Enhancements for the very-low-power regime (below 1 μW) rely on spin diodes [36] and backward tunnel diodes [37]. For typical input power between 1 μW and 1 mW, low-barrier Schottky diodes remain the most competitive and popular technology [1], [18], [25]. Due to parasitic losses, e_3 also decreases as the frequency increases [25]. The rectifier circuit topology also impacts e_3. A single diode is preferred at low power (1–500 μW), while multiple diodes (voltage doubler/diode bridge/charge pump) are favored above 500 μW [18], [38].

The efficiency also depends on the input power level and the output load variations. One method to minimize sensitivity to output load variation is to use a resistance compression network [39]. In addition, topologies using multiple rectifying devices, each optimized for a different range of input power levels, can enlarge the operating range versus input power variations and avoid, within the power range of interest, the saturation effect (which creates a sharp decrease in e_3) induced by the diode breakdown [40]. This can be achieved using a single-diode rectifier at low input power and a multiple-diodes rectifier at higher power.

The rectenna design is not the only factor influencing e_3. Due to the rectifier nonlinearity, the input waveform (power and shape) also influences e_3 in the low input power regime (1 μW–1 mW) [41]–[44], [47]. A 20-dB gain (in terms of $\mathrm{P_{DC,Rx}}$) of a multisine over a CW excitation at an average input power of –15 dBm was shown in [43]. The output filter is important as well, in relation to the tone separation, to boost the performance of the multisine waveform [45], [46]. High PAPR signals were also shown to be beneficial in [47]. It was argued in [48] that the instantaneous power variance is more accurate than PAPR for characterizing the effect of modulation on rectifier efficiency. Suitable signals and waveforms, therefore, exploit the nonlinearity to boost e_3 at low input powers and extend the WPT range [49].

Modulation also has an impact on e_3. In [50], quadrature phase-shift keying (QPSK) modulation was shown to be beneficial to e_3 compared to a CW in the low-power regime of –20–0 dBm. References [51] and [52] reported somewhat contradictory behaviors in the higher input power regime of 0–20 dBm, where PSK and quadrature amplitude modulation were shown beneficial to e_3 (compared to a CW in [51]) and detrimental in [52]. The work in [53] argues that there may or may not be an advantage when using multisines or other modulated signals, depending on the load and input power. Recent developments reported in [54] have found that, for low RF power (–17 dBm), the multisine signals do not improve the peak RF-to-dc conversion efficiency e_3 over a CW signal if the optimal load is selected for each case. However, multisine signals maintain the peak e_3 over higher output voltage (i.e., larger loads) and, consequently, enable more efficient dc-to-dc voltage boost or even eliminate the need for the voltage booster in the RF power receiver.

DC-to-DC Conversion Efficiency

DC-to-dc conversion efficiency e_4 is enhanced by dynamically tracking the rectifier's optimum load; for example, dc-to-dc switching converters dynamically track the maximum power point condition [55], [59]. Due to the variable load on the rectenna, changes in diode impedance with power level, and the rectifier's nonlinearity, the rectifier's input impedance becomes highly variable, which makes matching difficult—not to mention that joint optimization of the matching and load is necessary for multisine signals [53]. Nevertheless, multisine signals could be helpful in enabling more efficient dc-to-dc voltage boost [54].

The most important figures of merit for determining the low operating boundaries of ULP dc-to-dc converters are the intrinsic power consumption and minimum input voltage during either steady-state operation or from a cold start-up. Existing commercial ICs have demonstrated start-up voltages of a few tens of millivolts with the help of an external transformer [56]. Further, more recent discrete-component solutions show power consumption down to 1 μA and input voltages down to few tens of millivolts [57], while CMOS implementations reach hundreds nanowatts of power [58].

End-to-End Power Transfer Efficiency

Maximizing e is not achieved by maximizing e_1, e_2, e_3, and e_4 independently of one another and thereby simply concatenating the previously described techniques. This is because e_1, e_2, e_3, and e_4 are coupled due to the rectifier's nonlinearity, especially at an input power range of 1 μW–1 mW. Because e_3 is a function of the input signal shape and power to the rectifier, it is also a function of the transmit signal (beamformer, waveform, modulation, and power allocation) and the wireless channel state. Similarly, e_2 depends on the transmit signal and the channel state, as does e_1, because it is a function of the transmit signal's PAPR.

Some recent approaches optimize the system using numerical software tools based on a combination of full-wave analysis and nonlinear harmonic balance techniques to account for nonlinearities and electromagnetic couplings [19], [60]. This approach would provide very high accuracy but has the drawback of being applicable only for offline system optimization not for an adaptive WPT (in which the transmit signal is adapted every few milliseconds as a function of the channel state), let alone for an entire WPT network with multiple transmitters and receivers.

A unified wireless information and power transfer (WIPT) design could evolve unobtrusively in between those two extremes, making the best use of the RF spectrum/radiations and of network infrastructure to communicate, energize, and, hence, outperform traditional systems.

Observations

We can now make several observations:

- Considerable technical effort in the wireless power literature has been directed toward the design of the energy harvester, but much less emphasis has been put on signal design for WPT. The emphasis has remained on point-to-point (single-user) transmission.
- Research has recognized the importance of nonlinearity for the rectenna in WPT system design but has focused, to a great extent, on decoupling the WPT design by optimizing the transmitter and the energy harvester independently of one another.
- Multipath and fast fading, critical in NLoS, have been ignored, despite their playing a key role in wireless transmissions and having a huge impact on the signal shape and power at the rectenna's input. Recall that multipath has consequences in that the transmit and receive (at the input of the rectenna) waveforms are completely different.

- WPT design has remained very much centered around an open-loop approach, with the waveform being static and beamforming relying on tag localization not on channel state.
- The design of the transmit signals is heuristic (with conclusions based exclusively on observations obtained from measurements using various predefined and standard waveforms), but no systematic approach and performance bounds exist to design and evaluate them. The waveform and beamformer have been studied independently, despite being part of the same transmit signal.

Tackling the Challenges

Effectively tackling the challenges discussed so far will require several developments:

- *A closed-loop and adaptive WPT architecture* with a *reverse communication link* from the receiver to the transmitter that supports various functions, such as channel feedback/training, energy feedback, and charging control. The transmitter should be able to flexibly adjust the transmission strategy, jointly optimized across space and frequency (through beamforming and waveform) in accordance with the channel status [commonly called *channel state information* (*CSI*)], rendering state-of-the-art multiple-input/multiple-output (MIMO) processing an indispensable part of WPT. An example of a closed-loop and adaptive WPT architecture is shown in Figure 2.
- *A systematic approach to design and optimize the signal at the transmitter*, as a function of the channel (encompassing beamforming and waveform) to maximize $e_2 \times e_3$ subject to transmit power and PAPR constraints. This requires that the rectifier's nonlinearity and the wireless channel be captured as part of signal design and optimization. Such a systematic design methodology will lead to the implementation of efficient strategies as part of the "Transmission Optimization" module in Figure 2.
- *A link and system design approach that takes wireless power from a rectenna paradigm to a network paradigm*, with multiple transmitters and/or receivers. Instances of such network architectures may be a deployment of colocated transmit antennas delivering power to multiple receivers or a dense and distributed deployment of well-coordinated antennas/transmitters, as illustrated in Figure 3.

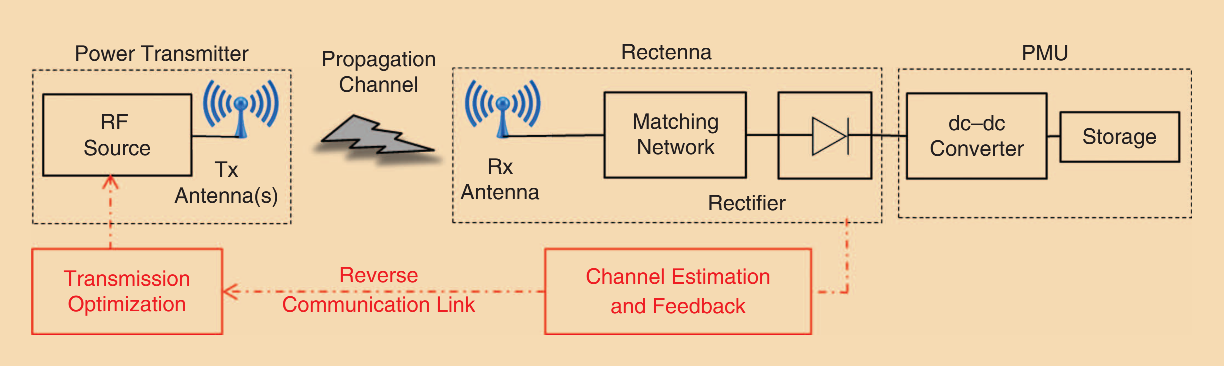

Figure 2. *A block diagram of a closed-loop and adaptive WPT architecture.*

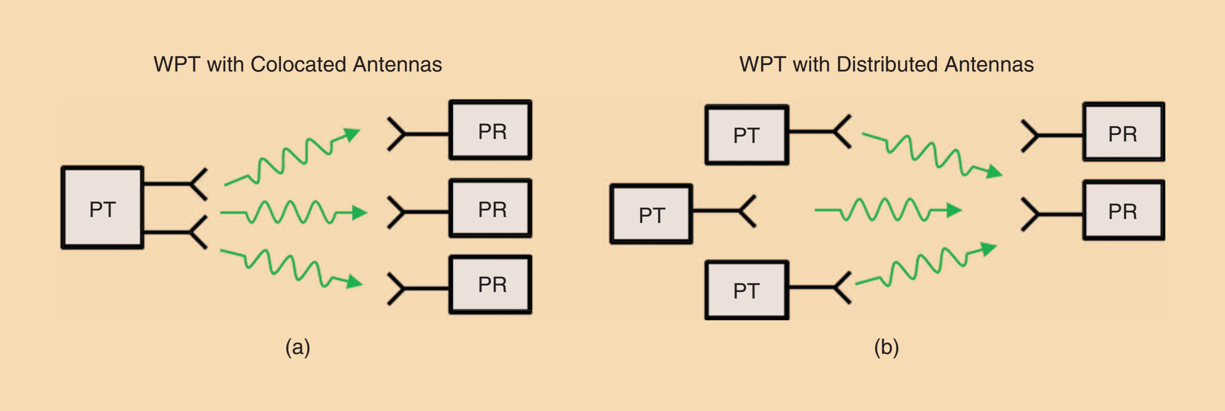

Figure 3. *An illustration of a WPT network with (a) colocated and (b) distributed transmit antennas and multiple receivers. PT: power transmitter; PR: power receiver.*

Leveraging Ideas from Wireless Communications

The fundamental limits of any communication network design lie in information and communication theories that derive the capacity of wireless channels (e.g., point-to-point, broadcast, multiple access, and interference channel with single and multiple antennas) and identify transmission and reception strategies to achieve that capacity, most commonly under the assumption of a linear communication channel with additive white Gaussian noise. Research beginning in the 1970s and continuing until the early 2000s emphasized link optimization, i.e. maximizing point-to-point spectral efficiency (bits/s/Hz) with advances in modulation and waveforms, coding, MIMO, CSI feedback and link adaptation, and communication over a (multipath) fading channel. CSI feedback enables a transmission strategy to be dynamically adapted as a function of the channel state and leads to a drastic increase in rate and also to reduced complexity in the receiver design.

The emphasis in 4G design shifted toward system optimization, with a more interference-centric system design. MIMO evolved into a multilink/user/cell MIMO. Multiple users are scheduled in the same time-frequency resource onto (ideally) noninterfering spatial beams. This has led to significant features such as multiuser MIMO, multiuser fairness and scheduling, and multipoint cooperation. The availability of accurate CSI at the transmitter (CSIT) is also crucial in multiuser, multiantenna wireless communication networks for the design of efficient beamforming and interference-management solutions. Some promising technologies consist of densifying the network by adding more antennas either in a distributed or a colocalized manner. The distributed deployment leads to a dense network (with a high-capacity backbone) that requires interference mitigation techniques, commonly called *coordinated multipoint transmission and reception* in the 3rd Generation Partnership Project and classified into 1) joint processing (or network MIMO) and 2) coordinated scheduling, beamforming, and power control. Colocalized deployment leads to massive/large-scale MIMO, in which a base station designs pencil beams (with large beamforming gain) to serve its own users, employing per-cell design rules while simultaneously avoiding intercell interference. Readers may consult [61] for more on the fundamentals and design of state-of-the-art MIMO wireless communication networks.

Observations

Again, we can make several observations.

- Wireless power and communication systems that share the same medium and techniques inspired by communications (e.g., MIMO, closed-loop operation, CSI acquisition, and transmitter coordination) are expected to be useful to WPT.
- Existing techniques developed for wireless communications cannot be applied directly to wireless power, due to their distinct design objectives (rate versus energy), practical limitations (hardware and power constraints), receiver design and sensitivities (e.g., –30 dBm for a rectenna versus –60 dBm for information receivers), interference (beneficial in terms of energy harvesting but detrimental in communications), and models (e.g., rectifier nonlinearity).

WPT Signal and System Design

Aside from the traditional WPT RF design, a new and complementary line of research on communications and signal design for WPT has recently emerged in the communication literature [62] and is briefly reviewed next. This includes the design of efficient transmit signals (including waveform, modulation, beamforming, and power allocation), CSI acquisition strategies, multiuser transmission strategies, integration with communications, and system prototyping. Importantly, the nonlinearity of the rectifier must be captured as part of the signal and the system design and optimization because it induces coupling among the various efficiencies.

Let us first consider a point-to-point scenario with a single transmitter and receiver. The first systematic approach toward signal design in adaptive closed-loop WPT was proposed in [63] and [64], where the transmit signal—accounting jointly for multisine waveform, beamforming, and power allocation—is optimized as a function of the CSI to maximize $e_2 \times e_3$, subject to optional transmit PAPR constraints. Such a signal design uniquely resolves some limitations presented in the WPT literature by optimally exploiting a beamforming gain, a frequency diversity gain (because of the frequency selectivity of the wireless channel), and rectifier nonlinearity. The rectifier's nonlinearity was modeled using a Taylor expansion of the diode characteristic, which is a popular model in the RF literature [42], [38]. The phases of the optimized waveform can be computed in closed form, while the magnitudes result from a nonconvex optimization problem that can be solved with convex optimization techniques, using the so-called reverse geometric program (GP).

Multiple observations were made in [63] and [64]. First, it was observed that the derived adaptive and optimized signals accounting for the nonlinearity are more efficient than nonadaptive and nonoptimized multisine signals (as used in [41]–[44]). Second, the rectifier's nonlinearity was shown to be essential in the design of efficient wireless power signals: ignoring it leads to inefficient signal design in the low-power regime. Third, the optimized waveform design favors a power allocation over multiple frequencies, and those with stronger frequency-domain channel gains are allocated more power. This power allocation results from a compromise between exploiting the rectifier's nonlinearity and the channel frequency selectivity. Fourth, multipath and frequency-selective channels were shown to have a significant impact on the dc output power and waveform design. Although multipath is detrimental to performance with nonadaptive waveforms, it is beneficial with channel-adaptive waveforms and leads to a frequency diversity gain.

As an example, Figure 4(a) shows the frequency response magnitude of a realization of the wireless channel over a 10-MHz bandwidth. It considers a multisine waveform with 16 sinewaves uniformly spread within the 10 MHz. Assuming that knowledge of this channel realization has been acquired by the transmitter (through channel estimation and feedback), the magnitudes of the optimized waveform on the 16 frequencies can be computed and then displayed [Figure 4(b)]. In contrast to the waveforms commonly used in the RF literature [41]–[44], [47], which are nonoptimized and nonadaptive to the channel state, the optimized adaptive waveform has a tendency to allocate more power to frequencies exhibiting larger channel gains.

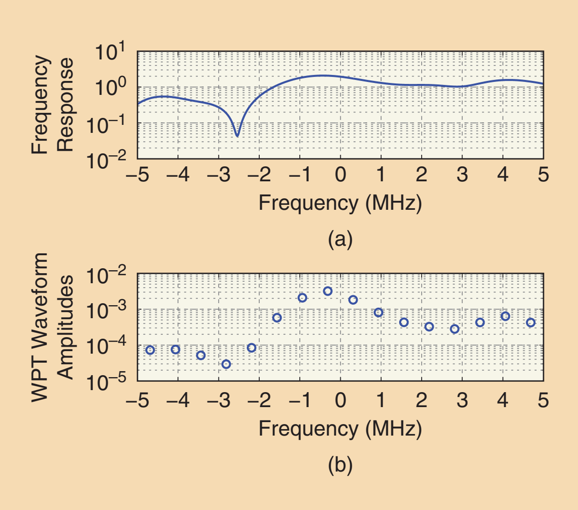

Figure 4. *The (a) frequency response of the wireless channel and (b) WPT waveform magnitudes (N = 16) for a 10-MHz bandwidth [64].*

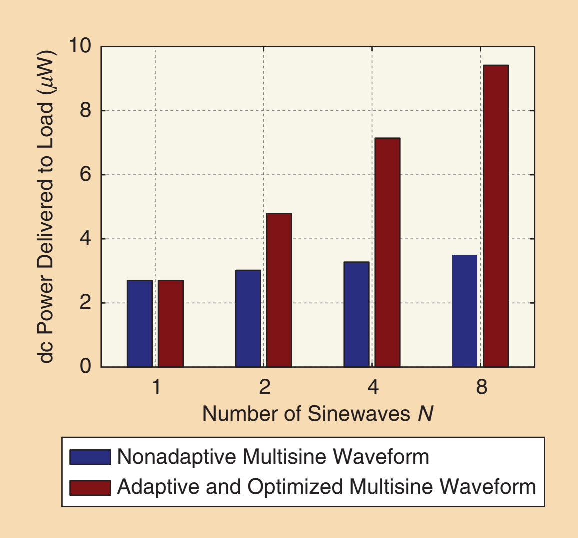

Figure 5. *The dc power versus number of sinewaves N for adaptive and nonadaptive waveforms.*

The performance benefits of these optimized channel-adaptive multisine waveforms over the nonadaptive design approach (i.e., in-phase multisine with uniform power allocation) in [41]–[44] has been validated using ADS and PSpice simulations with a single-series rectifier in a Wi-Fi-like environment at 5.18 GHz for an average input power of approximately –12 dBm [63] and –20 dBm [64], [65]. As illustrated in Figure 5, for a single transmit antenna and a single series rectifier subject to an average input power of –12 dBm and multipath fading, the gains (over the nonadaptive design) in terms of harvested dc power are significant, with over 100% gains for four sinewaves and an approximately 200% gain for eight sinewaves. Significant performance gains have also been validated in [64] at –20-dBm average input power for various band widths and in the presence of multiple transmit antennas where waveform and beamforming are jointly designed. Moreover, [65] showed that the systematic signal design approach of [64] is applicable as well and provides gains (100–200%) in a wide range of rectifier topologies, such as single series, voltage doubler, and diode bridge. Details on circuit design and simulation assumptions can be found in [64] and [65].

The systematic and optimized signal designs of [64] also show that, contrary to what is claimed in [44] and [47], maximizing PAPR is not always the right approach for designing an efficient wireless power signal. High PAPR is a valid metric for WPT with multisine waveforms if the channel is frequency-flat but not in the presence of multipath and frequency selectivity. This can be inferred from Figure 5, where the nonadaptive multisine waveform leads to a much lower dc power despite exhibiting a significantly higher transmit PAPR compared to the adaptive waveform. The adaptive waveform is unlikely to allocate power uniformly across all sinewaves because it emphasizes the ones corresponding to a strong frequency-domain channel. This leads to waveforms whose PAPR is lower than a nonadaptive in-phase multisine waveform with uniform power allocation.

The results in [64] also highlight the potential of a large-scale multisine, multiantenna closed-loop WPT architecture. In [66] and [67], such a promising architecture was designed and shown to be an essential technique for enhancing *e* and increasing the range of WPT in low-power devices. It enables highly efficient very-far-field wireless charging by jointly optimizing transmit signals over a large number of frequency components and transmit antennas, thereby combining the benefits of pencil beams and waveform design to exploit the large beamforming gain of the transmit antenna array and the nonlinearity of the rectifier at long distances. The challenge here is the large-dimensionality problem, which calls for a reformulation of the optimization problem. The new design enables orders of magnitude of complexity reduction in signal design compared to the reverse GP approach. Another low-complexity adaptive waveform design approach expressed in closed form (and, hence, suitable for practical implementation) has been proposed in [65] and shown to perform close to the optimal design. Figure 6 illustrates how the rectifier output voltage decreases with range for several values of the number of sinewaves N and transmit antennas M in the multisine transmit waveform. By increasing both N and M, the range is expanded, thanks to the optimized, channel-adaptive multisine waveforms that jointly exploit a beamforming gain, a frequency diversity gain, and rectifier nonlinearity.

Despite the presence of many transmit antennas and sinewaves, a single receive antenna and rectifier per terminal have been assumed in the previously described signal design and optimization. A fruitful area of research would involve understanding how the signal design could be extended to multiple receive antennas, which brings the problem of RF or dc combining or mixed RF–dc combining to the forefront [68]–[70].

Discussions on this topic have so far assumed deterministic multisine waveforms. It is important, however, to understand how modulated waveforms perform (compared to deterministic waveforms) and how modulation could be tailored specifically for WPT to boost end-to-end power transfer efficiency. This would also open the way to understanding how to design unified and efficient signals for simultaneously transmitting information and power. A modulated waveform exhibits randomness, and this randomness has an impact on the amount of harvested dc power. The work discussed in [72] shows that, for single-carrier transmission, modulation using circularly symmetric complex Gaussian (CSCG) inputs is beneficial to the performance, compared to an unmodulated CW. This gain comes from the large fourth-order moment offered by CSCG inputs, which is exploited by the rectifier's nonlinearity. Even further gain can be obtained using asymmetric Gaussian inputs [73] and flash signaling [74].

Flash signaling is promising as it leads to modulation with a low probability of high-amplitude signals and has been shown to significantly boost RF-to-dc conversion efficiency over various baselines (with gains of more than 200%) [74]. On the other hand, for multicarrier transmission, modulation using CSCG inputs was shown in [72] to be less efficient than multisine because of the independent randomness across carriers, which leads to random fluctuations. This contrasts with the periodic behavior of deterministic multisine waveforms, which are more suitable for toggling the rectifier periodically. In [72], the authors showed that PAPR is not an appropriate metric to use for assessing the suitability of a general modulated waveform for WPT. Despite this recent progress on signal design for WPT, the optimum input distribution, modulation, and waveform remain unknown.

We now understand that a systematic waveform design (including modulation, beamforming, and power allocation) is a key technique to jointly exploit beamforming gain, channel-frequency selectivity, and rectifier nonlinearity and so enhance the end-to-end power transfer efficiency and range of WPT. One challenge is that those waveforms have been designed assuming perfect CSI at the transmitter. In practice, this is not the case, and the transmitter should find ways to acquire the CSI. Various strategies exist, including forward-link training with CSI feedback, reverse-link training via channel reciprocity, and power probing with limited feedback [62].

The first two are similar to strategies used in modern communication systems [61]. The third is more promising and tailored to WPT because it is implementable with very low communication and signal processing requirements at the terminal [75]. It relies on the harvested dc power measurement and a limited number of feedback bits for waveform selection and refinement [76]. In the waveform-selection strategy, the transmitter transmits over multiple time slots with a different waveform precoder within a codebook at each time slot, and the receiver reports the index of the precoder in the codebook that leads to the largest harvested energy. In the waveform-refinement strategy, the transmitter sequentially transmits two waveforms in each stage, and the receiver reports one feedback bit, indicating an increase/decrease in the harvested energy during this stage. Based on multiple one-bit feedback, the

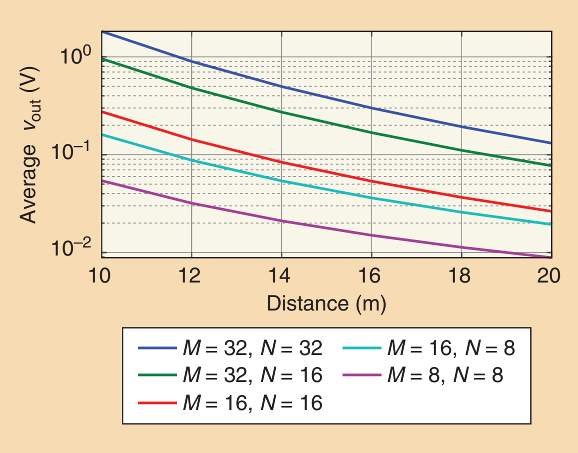

Figure 6. *Rectifier average output voltage as a function of the transmit–receive distance [67].*

transmitter successively refines waveform precoders in a tree-structured codebook over multiple stages.

Wireless power networks are not limited to a single transmitter and receiver. We now consider the presence of a single transmitter and multiple users/receivers, with each receiver having one rectenna. In this multiuser deployment, the energy harvested by a given rectenna depends on the energy harvested by the other rectennas; i.e., a given waveform may be suitable for one rectenna but inefficient for another. Therefore, a tradeoff must be considered between the energy harvested by the different rectennas. The energy region formulates this tradeoff by expressing the set of all rectenna-harvested energy that can be achieved simultaneously, which is written mathematically as a weighted sum of harvested energy, where, by changing the weights, we can operate on a different point of the energy region boundary. Strategies to design WPT waveforms in this multiuser/rectenna deployment are discussed in [64] and [67].

Figure 7 illustrates such an energy region for a two-user scenario with a multisine waveform spanning 20 transmit antennas and ten frequencies. The key takeaway here is that, by optimizing the waveform to jointly deliver power to the two users simultaneously, we obtain an energy region ("weighted sum") that is larger than the one achieved by a timesharing approach [for example time-division multiple access (TDMA)], where the transmit waveform is optimized for a single user at a time and each user is scheduled to receive energy during a fraction of the time.

Moving toward an entire network composed of many transmitters and receivers, a network architecture needs to be defined [62]. This may consist of all transmitters cooperating to jointly design the transmit signals for multiple receivers or of local coordination among transmitters such that a given receiver is served by a subset of transmitters (or, in the simplest scenario, where each receiver is served by a single transmitter). This leads to different resource-allocation and charging control requirements and strategies (centralized versus distributed) in terms of CSI sharing and acquisition at the different transmitters. The results in [62] show that distributing antennas across a coverage area (as in Figure 3) and enabling cooperation among them distributes energy more evenly in space and, therefore, potentially enhances the ubiquitous accessibility of wireless power as compared to a colocated deployment. It also avoids creating strong energy beams in the direction of users, which is desirable from a health and safety perspective.

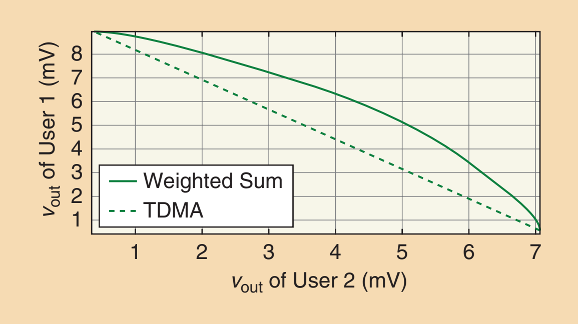

Figure 7. *The two-user energy region with M = 20 and N = 10 [67].*

Demonstrating the feasibility of these signal and system designs through prototyping and experimentation remains largely an open challenge. Meeting this challenge requires implementing a closed-loop WPT architecture with real-time over-the-air transmission based on a frame structure that switches between a channel-acquisition phase and a WPT phase. The channel acquisition needs to be performed at the millisecond level (similar to CSI acquisition in communication). Different blocks need to be built: channel estimation, channel-adaptive waveform design, and rectenna. The first prototype of a closed-loop WPT architecture based on channel-adaptive waveform optimization and dynamic channel acquisition, as illustrated in Figure 8, was recently reported in [77] with further enhancements in [78].

Importantly, all experimental results validate the theory developed in [64] and [65] and fully confirm the following observations:

1) Diode nonlinearity is beneficial to WPT performance and is to be exploited in systematic waveform design.
2) The wireless propagation channel has a significant impact on signal design and system performance.
3) CSI acquisition and channel-adaptive waveforms are essential to boost the performance in frequency-selective channels (as in NLoS scenarios).
4) Larger bandwidths benefit from a channel frequency diversity gain.
5) PAPR is not an accurate metric to assess and design waveforms for WPT in general frequency-selective channels.

Figure 9 illustrates the performance gain of a channel-adaptive multisine waveform versus nonadaptive multisine waveform in an NLoS deployment with a single antenna at the transmitter and receiver. We note the significant boost of the average harvested dc power: 105% at the rectenna output over an open-loop WPT architecture with a nonadaptive multisine waveform (having the same number of sinewaves) and 170% over a CW. Further prototyping, experimentation, and validation of WPT signal designs—including waveform, modulation, and beamforming in various deployment scenarios (LoS, NLoS, and mobility)—can be found in [78].

Ultimately, wireless power and wireless communications must be integrated. This calls for a unified WIPT paradigm. WIPT can be categorized into three different types [79]:

- *Simultaneous WIPT (SWIPT):* Energy and information are simultaneously transferred in the

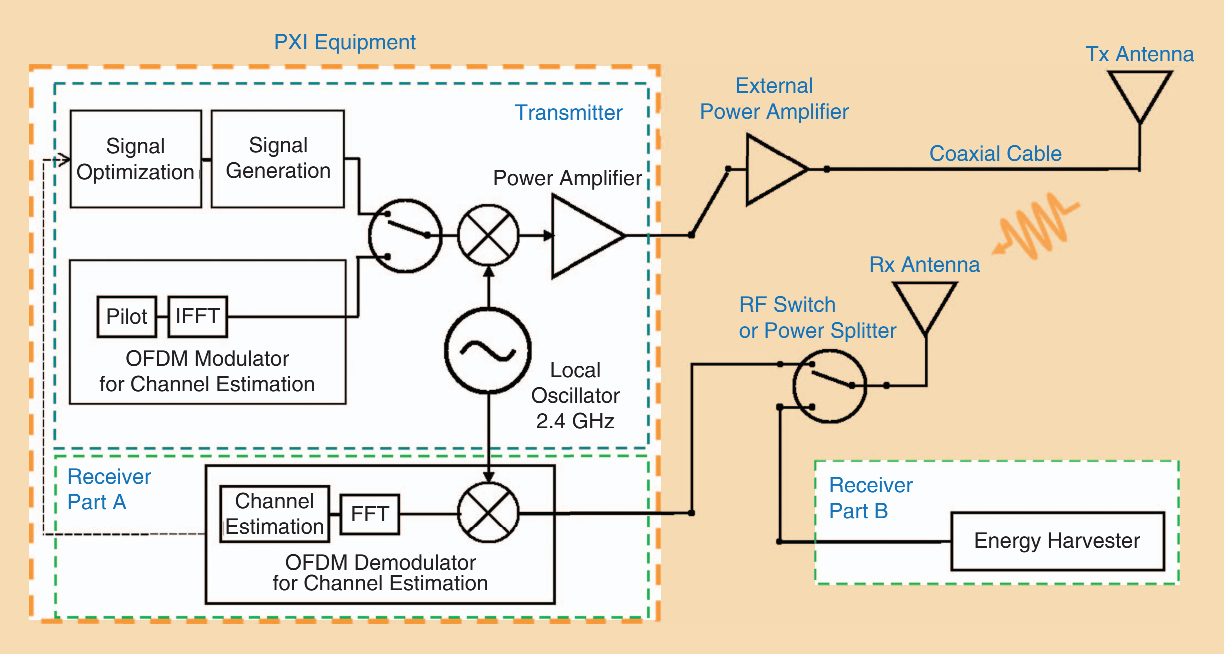

Figure 8. *The prototype architecture with three key modules: signal optimization, channel acquisition, and energy harvester [77], [78]. FFT: fast Fourier transform; IFFT: inverse FFT; OFDM: orthogonal frequency-division multiplexing.*

downlink from one or more access points to one or more receivers. The energy receiver(s) [ER(s)] and information receiver(s) [IR(s)] can be colocated or separated. In SWIPT with separated receivers, the ER and IR are different devices: the ER is a low-power device being charged; the IR is a device receiving data. In SWIPT with colocated receivers, each receiver is a single low-power device that is simultaneously being charged and receiving data.

- *Wirelessly powered communication network:* Energy is transferred in the downlink, and information is transferred in the uplink. The receiver is a low-power device that harvests energy in the downlink and uses it to send data in the uplink.
- *Wirelessly powered backscatter communication (WPBC):* Energy is transferred in the downlink, and information is transferred in the uplink; however, backscatter modulation at a tag is used to reflect and modulate the incoming RF signal for communication with a reader. Because tags do not require oscillators to generate carrier signals, backscatter communications benefit from orders-of-magnitude lower power consumption than conventional radio communications. RFID is an example of WPBC.

A major challenge in WIPT is to characterize the fundamental tradeoff between conveying information and energy (or harvested dc power) wirelessly [80]–[82] and identify corresponding transmission and reception strategies.

A tradeoff between rate and energy exists because the transmit signal used to maximize rate is not necessarily the same as the one that maximizes energy. A simple example is obtained when we want to transmit information and energy simultaneously across multiple subbands on a frequency-selective channel [81]. To maximize the amount of energy collected at the receive antenna (and, therefore, maximize e_2), one would transmit all power on the strongest subband, i.e., the one corresponding to the strongest frequency-domain channel. Unfortunately, such a strategy does not necessarily maximize the information rate. To maximize this rate, it is more efficient to transmit information across multiple subbands and allocate power across subbands according to the well-known

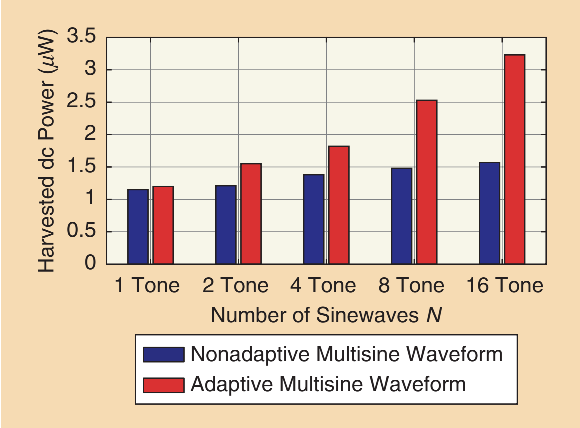

Figure 9. *Harvested dc power using the architecture of Figure 8 in an indoor NLoS deployment as a function of N (N sinewaves whose frequencies are uniformly spread within a 10-MHz bandwidth) [78].*

water-filling algorithm [83]. Depending on the specific values of the rate and energy level to be achieved, the transmitter would have to properly adjust the amount of power across subbands [81].

A rate–energy tradeoff is also induced by the receiver architecture [82]. The simplest receiver would rely on time switching between colocated information decoder and energy harvester receivers, where the information decoder receiver is a conventional baseband information decoder, while the energy harvester receiver's structure consists of a rectifier and PMU. In this case, the transmitter divides the transmission block into two orthogonal time slots, one for transferring power and the other for transmitting data. At each time slot, the transmitter could optimize its transmit waveform for either power transfer or information transmission. Then, the receiver switches its operation periodically between harvesting energy and decoding information in the two time slots. By varying the length of the power transfer time slot (jointly with the transmit signals), different tradeoffs between rate and energy could be realized. More complicated receivers based, for example, on a power splitter also exist and result in different tradeoffs. Readers are referred to [79] for an overview of the fundamentals of WIPT and how the transmit signals and the receiver architecture affect the rate–energy tradeoff for various models of the energy harvester.

One crucial aspect of WIPT is the underlying energy harvester model. Leveraging these wireless power signal designs, it has been shown that rectifier nonlinearity has a profound impact on the design of WIPT [71]–[74], [79]. In contrast with the classical CSCG input distribution that is used extensively in communication [83], rectifier nonlinearity leads to input distributions that are asymmetric Gaussian (or even based on time sharing between Gaussian and flash signaling in single-carrier transmission over frequency-flat channels [73], [74]) and to nonzero mean Gaussian in multicarrier transmissions [71], [72]. Those observations have also triggered the design of novel modulations for WIPT [84]. It was shown that an asymmetric PSK modulation enlarges the rate–energy tradeoff compared to conventional symmetric PSK modulation. The optimal input distribution and transmit signal strategies for WIPT in general settings remain unknown. Those results stand in sharp contrast with earlier results in [80]–[82] that ignore rectifier nonlinearity and therefore rely on the CSCG input distribution that is conventionally used in wireless communications.

Observations

First, the previously discussed results show the huge potential for 1) comprehensive signal and system design and optimization approaches for efficient WPT and 2) WIPT that accounts for the unique characteristic of wireless power, namely nonlinearity.

Second, nonlinearity radically changes the design of WPT and WIPT in three ways: 1) it leads to a WIPT design that differs from that of conventional wireless communication; 2) it favors a different input distribution, signal design, transceiver architecture, and use of the RF spectrum; and 3) it is beneficial for increasing the rectifier output dc power and enlarging the rate–energy region.

Third, an adaptive signal design approach provides a different paradigm compared to traditional WPT designs. It leads to an architecture in which the rectenna is, as much as possible, fixed (for example, with a fixed load) but the transmit signal is adaptive—in contrast to the approach in the RF literature, where the waveform is fixed and the rectenna/PMU is adaptive (for example, dynamic load control). Because the wireless channel changes quickly (10-ms order), it can be impractical for energy-constrained devices to dynamically compute and adjust the matching and load as a function of the channel. Even though the two approaches are complementary, the adaptive signal approach makes the transmitter smarter and decreases the need for power-hungry optimization of/at the devices. Nevertheless, adaptation implies acquiring CSIT, which is an important challenge to be addressed. Ultimately, it is envisioned that an entire end-to-end optimization of the system should be conducted, likely resulting in an architecture in which the transmit signals and the rectennas adapt themselves dynamically as a function of the channel state.

Conclusions

Integrated signal and system optimization was introduced as a strategic approach for realizing the first generation of a mobile power network and to enable energy autonomy for pervasive devices, such as smart objects, sensors, and embedded systems, over a wide range of operating conditions. We have shown that the nonlinear nature of this design problem (considering both the transmitter and receiver) must be accounted for at the signal as well as circuit-level design. New system architectures could enable WPT and WIPT, while enhancing the power transfer efficiency at ultralow power levels. Techniques for dynamic tracking of the channel changes need to be exploited to adaptively modify the transmitted energy in terms of both its waveform shape and intensity, with the twofold advantage of reducing the complexity of the rectenna and of the PMU design while keeping the rectenna itself in its own optimum operating conditions.

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