Smart RF Energy Harvesting Communications: Challenges and Opportunities

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ABSTRACT

RF energy harvesting (RFH) is emerging as a potential method for the proactive energy replenishment of next generation wireless networks. Unlike other harvesting techniques that depend on the environment, RFH can be predictable or on demand, and as such it is better suited for supporting quality-of-service-based applications. However, RFH efficiency is scarce due to low RF-to-DC conversion efficiency and receiver sensitivity. In this article, we identify the novel communication techniques that enable and enhance the usefulness of RFH. Backed by some experimental observations on RFH and the current state of the art, we discuss the challenges in the actual feasibility of RFH communications, new research directions, and the obstacles to their practical implementation.

INTRODUCTION

In recent times, RF energy harvesting (RFH) has emerged as a promising technology for alleviating the node energy and network lifetime bottlenecks of wireless sensor networks (WSNs). The RF radiation pattern is generally wide-angled; radio waves can simultaneously carry information and energy, and the radiation directivity can be electronically steerable. These features have been exploited in multihop energy transfer (MHET) as well as combining it with data transfer over the same RF signal (called simultaneous wireless information and power transfer, or SWIPT), without requiring critical alignment of the nodes [1, 2]. Besides, RFH has found applications in cognitive radio networks, wireless body area networks, and other wireless charging systems [3].

In RFH, RF wave radiations in the frequency range 3 kHz to 300 GHz are used as energy carriers. The amount of electrical energy that can be harvested is dependent on the power being emitted from the RF source, the antenna gains of the RF source and the receiving device, the distance of the receiving antenna from the RF source antenna, path loss exponent, and the RF-to-DC rectification efficiency η_{RF-DC}. The received electrical power is

$$P_R^{DC} = (\eta_{RF-DC})P_R,$$

where P_R is the received RF power that can be calculated using the Friis transmission equation.

RF energy sources can be classified into two categories:

- *Ambient RF source*: Ambient RF energy sources are not actually dedicated to RF energy transfer (RFET), and this RF energy is freely available. The frequency range of ambient RF transmission is 0.2–2.4 GHz, and this includes most of the radiations from domestic appliances (e.g., television, Bluetooth, WiFi).
- *Dedicated RF source*: This on-demand supply generally has a relatively higher power density due to directional transmission, and it is used to recharge nodes that require predictable and high amounts of energy. The energy transfer is done in the license-free industrial, scientific, and medical (ISM) frequency bands.

As RFH from dedicated RF sources, also known as RFET, is fully controllable, it is better suited for supporting applications with quality of service (QoS) constraints.

While RFET shows several promising directions and has an advantage over non-radiative wireless energy transfer in terms of relaxed coupling/alignment requirements [4], RFH suffers from various losses, including path loss, energy dissipation, shadowing, and fading. The problem is compounded by low energy reception sensitivity, restriction of maximum RF energy radiation due to human health hazards, and sharply decreasing RF-to-DC conversion efficiency at low receive powers. These RFH constraints place additional challenges compared to wireless data transfer because the information reception sensitivity is higher by a few orders of magnitude (typically –60 dBm in data reception vs. –10 dBm in RFH). This implies that with the current state of devices and RF circuits technologies, some applications may have limited practical utility. For example, the wireless energy plus

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data transfer paradigm in two-hop decode-and-forward relay mode may not work with conventional inter-node distances (a few tens of meters) because the currently realizable energy transfer range is only on the order of 1 m.

The first goal of this article is to provide an overview of the recent developments toward improving RFH efficiency. Some novel approaches we discuss include increasing RFH circuit efficiency, multi-path energy routing (MPER), multi-antenna energy transmission, distributed beamforming techniques, and protocol-based optimization for cooperative energy transmission. Second, we provide experimental insight on the practical implementations of some of these strategies for enhancing RFH efficiency and their corresponding implications, followed by the current theoretical practices in this regard. Next, driven by experimental insights and practical system parameter considerations, the article highlights the challenges and the allied systems research opportunities for various aspects of RFH communications.

IMPROVED RFH CIRCUITS

The general architecture of a RFH unit is shown in Fig. 1.

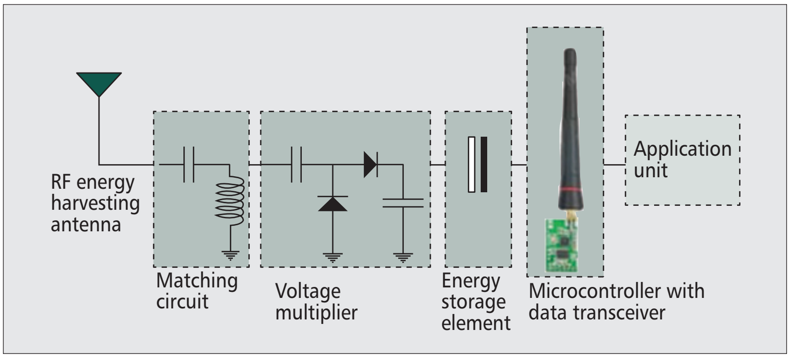


Figure 1. RF energy harvesting node.

The harvested energy is used to run a low-power micro-controller that processes the data from the application unit and controls the node's overall operation including information transmission and reception. The effectiveness of the RFH circuit is mainly determined by the RF-to-DC conversion efficiency and the DC output voltage. The conversion efficiency depends on the effectiveness of the antenna in collecting RF power, the precision of the matching circuit in energy conversion in the chosen frequency range, and the choice of the number of stages and diodes in the multiplier circuit.

IMPROVING RF-TO-DC CONVERSION EFFICIENCY

Maximum power transfer from the antenna to the voltage multiplier can be realized when the antenna output impedance and load impedance are conjugates of each other (impedance matching). For the RFH circuit to work efficiently at low input power, diodes with low turn on voltage are used in the voltage multiplier circuit. The number of multiplier stages also has a significant impact, as a higher number of stages provides higher load voltage but reduces the load current in the process, whereas a lower number of stages provide a faster charging, but the load voltage is significantly lowered. As the received input RF power is very low, Dickson topology comprising multiple stages of parallel capacitors is used for high RF-to-DC conversion efficiency [5].

Because of the nonlinearity of the diode characteristics, the energy conversion efficiency sharply reduces at low input RF power [5, 6]. A dual-stage design — one with seven stages that works well for low input RF power and the other with 10 stages for higher input RF power — was proposed in [5], and an optimization framework was used to decide on the switchover point between the two stages, resulting in about 20 percent efficiency improvement over the commercially available Powercast harvester. Recently, in [7] it was shown that the efficiency can be further improved by using a resonating L type matching circuit along with a low pass filter (LPF) at the last stage. The resonator circuit exhibits resonant behavior at a specific frequency that can strengthen the weak RF power signals significantly. The LPF at the last stage of the harvesting circuit reduces the output harmonics and ripples in the output voltage to increase the output DC voltage.

SCALABLE RECTENNA ARRAY

As the incident ambient RF waves vary in frequency, power density, polarization, and incidence angles, scalable rectenna arrays with optimized power management circuits have been discussed in [8] for increasing the RFH efficiency. For maximum DC power generation, inserting a transitional DC-DC converter with peak power tracking that can reconfigure the equivalent DC load of the rectenna array with varying input RF power has been suggested. Also, it has been noted that the amount of harvesting power can be maximized by optimizing the antenna cover area on printed circuit boards by placing a greater number of antenna patches.

While these are some of the RFH circuit and hardware related developments, the main focus in this article is the advances and opportunities involving communication systems.

EXPERIMENTAL INSIGHT ON SMART RFH COMMUNICATIONS

As noted earlier, RFH performance is limited by low energy reception sensitivity, low conversion efficiency at low input power, and the maximum allowable RF radiation power. In this section, we present some experimental observations on RFET with a special focus on multi-path energy routing (MPER), which provides efficient RFH communication by overcoming these hardware-based shortcomings. MPER helps improve RFH efficiency by first collecting the dispersed or dissipated RF energy transmitted by the RF source with the help of energy routers, and then directing it to the desired sensor node via paths other than the direct single hop path (Fig. 2a). These "energy routers" can be part of the network or may be introduced as optimally positioned

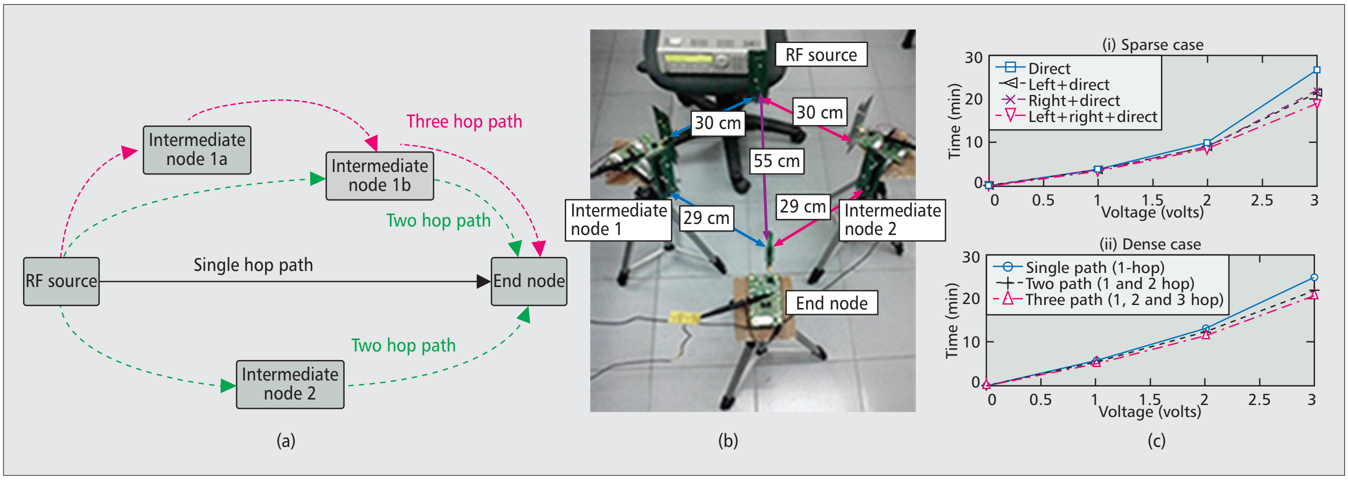


Figure 2. Multipath energy routing: a) block diagram of MPER; b) experiment setup for MPER in a sparse network; c) charging time comparison.

dummy nodes. MPER is based on the principle that multihop energy transfer (MHET) is beneficial to the energy transfer process.

MHET can improve energy harvesting efficiency by deploying relay nodes close to the target sensor node. The gain in MHET is achieved because of reduced path loss from the relay node to the end node, and improved RF-to-DC efficiency due to higher received power. Under the same principle, MHET can provide RFH range extension, which helps in implementing smarter RFH communications as it reduces the gap between the energy transfer and data transfer ranges. Feasibility studies in [2] showed that under certain optimum distance conditions, MHET can provide energy and time gains over direct energy transfer (DET). The improved performance of MHET over DET was experimentally demonstrated in [9]. The MHET experimental studies have been further extended to more generalized cases of MPER, which are discussed next.

MPER IN A SPARSE DEPLOYMENT SCENARIO

In a sparse deployment, the intermediate nodes' presence does not cause any blocking or shadowing to the direct line of sight (LOS) path to the end node. However, the intermediate node is in a disadvantageous position because it can receive a lesser amount of the signal. The MPER experimental setup is shown in Fig. 2b, where, to improve gain, two intermediate nodes are symmetrically placed on either side of the LOS path, constituting a three-path energy transfer.

The system specifications for the experimental setup are: HAMEG RF synthesizer transmitting +13 dBm at 915 MHz via a 6 dBi Powercast patch antenna; intermediate nodes composed of a Powercast P1110 EVB, a Mica2 mote, two Powercast 6 dBi patch antennas; and an end node comprising a Powercast P1110 EVB and a Powercast 1 dBi dipole antenna. Further details on the experimental setup can be found in [9]. The intermediate nodes store the energy harvested via a 6 dBi antenna in a 50 mF capacitor for running the Mica2 mote. They forward the energy in the form of data packets from the modified Mica2 mote to the end node via another 6 dBi antenna every time the capacitor is fully charged. For efficient RFET, the Mica2 mote has been reprogrammed to transmit packets continuously one after the other during the energy transmission state [9].

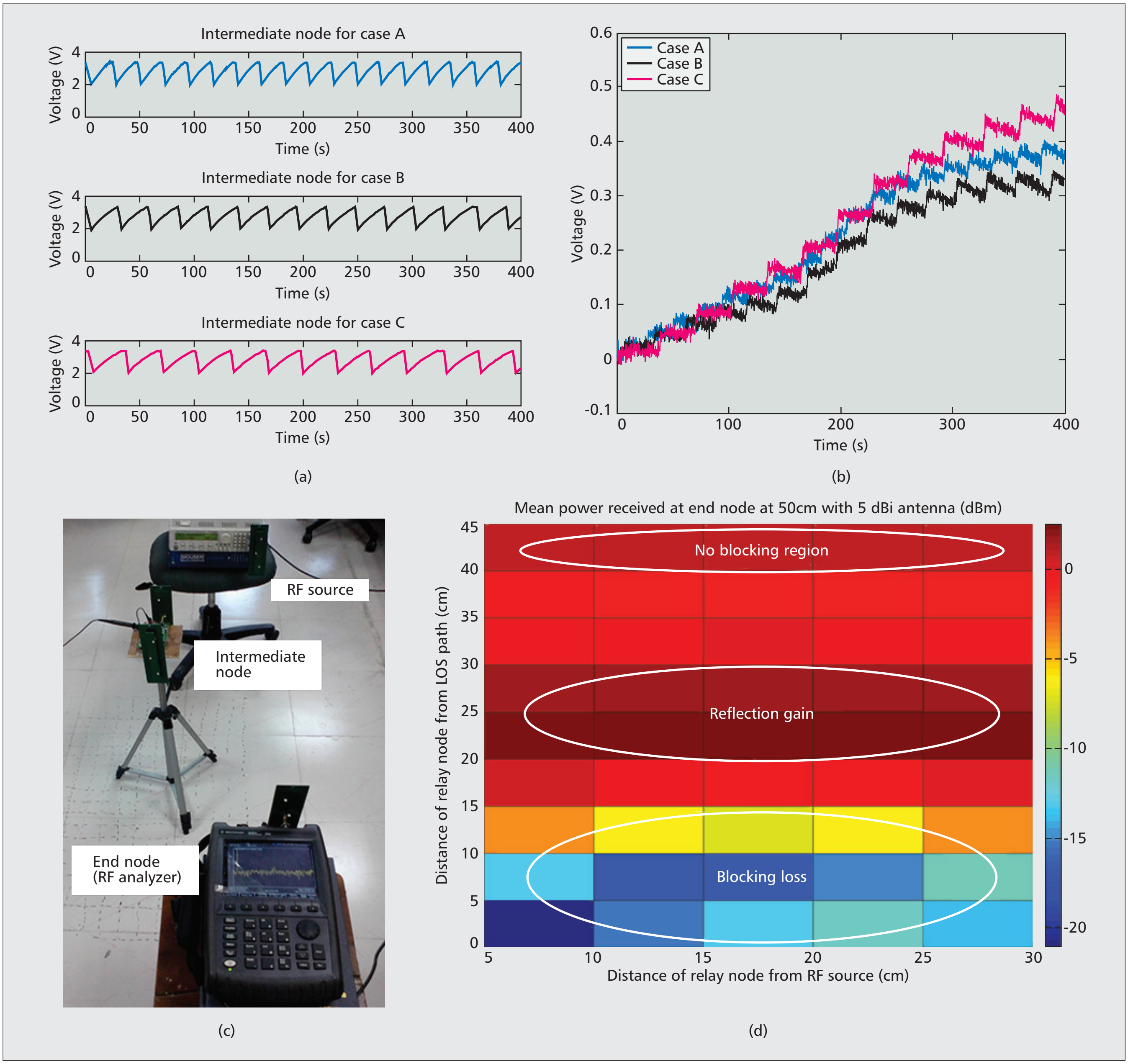
The MPER performances in the two-path scenarios (left+direct, right+direct) as well as in the three-path scenario (direct+left+right) are shown in Fig. 2c.i. Compared to DET, time saving to charge the end node's capacitor up to 3 V is about 18 and 28 percent, respectively, in the two-path and three-path cases. The energy gain is the same as the time gain, as energy and time are proportional for a constant power source.

MPER IN A DENSE DEPLOYMENT SCENARIO

In a dense deployment, charging one sensor node directly using LOS RF energy transmission may not be very efficient because of blocking/shadowing caused by the neighboring nodes. Hence, these intermediate nodes can be made to act like energy routers for the end node by adding transmission capabilities to them. Here, recharging multiple nodes simultaneously can also improve the overall system efficiency, as the sensor nodes near to the target sensor node can collect the otherwise dissipated energy.

The system specifications for the experimental setup are similar to the sparse scenario, except that a Hittite RF Synthesizer transmitting +23 dBm was used as the RF source, and the end node receives energy via a 6 dBi PCB patch antenna to overcome the blocking loss due to lower inter-node distances. The performance comparison in this case is shown with respect to the number of hops, which also demonstrates the feasibility of three-hop energy transfer. Referring to Fig. 2a, the intermediate nodes present are node 1a and node 1b. In the two-hop path, node 1a does not participate in RFET.

The representative results as plotted in Fig. 2c.ii show that both two-path (1-hop and 2-hop) and 3-path (1-hop, 2-hop, and 3-hop) MPER provide time gains of around 12 and 18 percent, respectively, over DET for charging the end node up to 3 V.



(a) (b) (c) (d)

Figure 3. Effect of intermediate node placement: a) number of on-off cycles comparison; b) contribution of relay ($V_{on} - V_{off}$); c) experiment setup; d) blocking characterization.

OPTIMAL RELAY PLACEMENT

As demonstrated earlier, MHET can improve RFET efficiency. However, this improvement is strongly influenced by the placement of relay nodes. To show the effect of relay node position, consider the following three cases in a 2-hop RFET (Fig. 3c) with RF source transmitting at +13 dBm over Powercast directional antennas at 915 MHz from a distance of 30 cm to the end node.

Case A: The relay node is closer to the RF source, so it harvests energy at a faster rate and forwards energy more frequently (with a higher number of on/off cycles; Fig. 3a). However, the energy received per cycle at the end node is very low due to a higher path loss.

Case B: The relay node is at the midway point to the end node. It harvests less energy compared to case A over a given time. Also, the energy received per forwarding cycle by the end node is lesser than case C due to higher path loss.

Case C: The relay node is closer to the end node. In this case the node harvests the least amount of energy over a given time, but the energy received per cycle by the end node is the highest due to minimum path loss. The overall performance of case C was noted to be the best, as shown in Fig. 3b. The average energy gain was noted to be about 10 percent over the worst case [9].

The above experimental study, however, calls for optimization formulations to find the optimum intermediate node positions to maximize RFET efficiency under different deployment

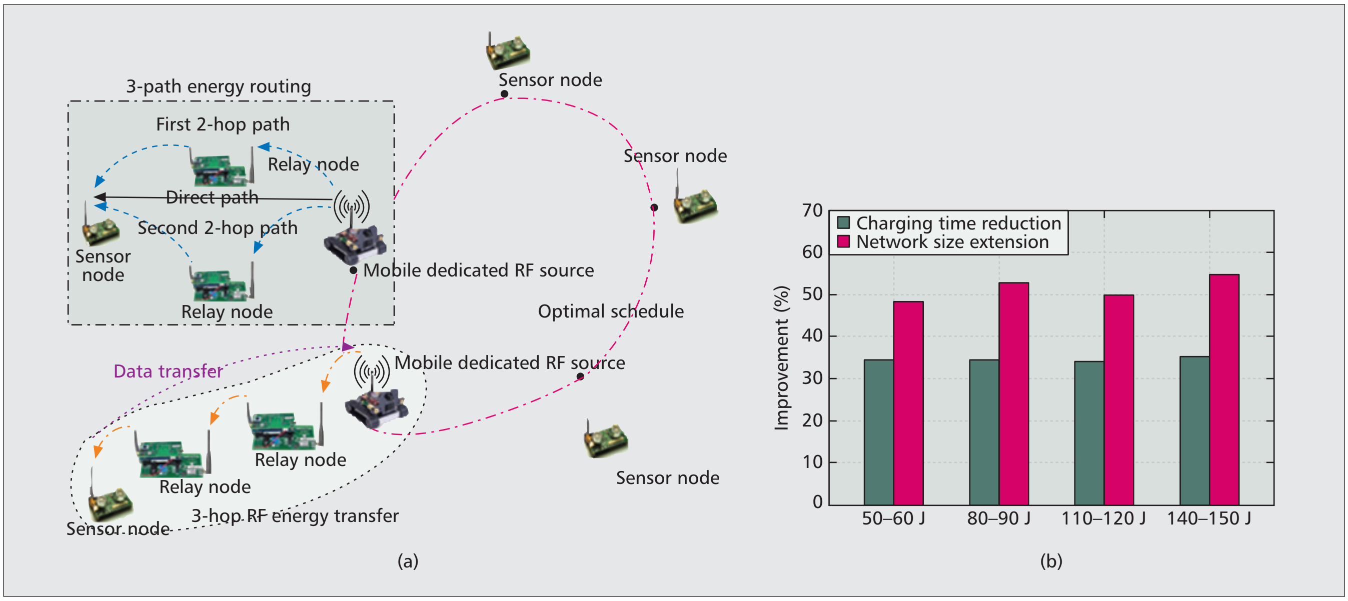


Figure 4. Networking consequence of improved RFH efficiency: a) quicker charging using dedicated RF source with MPER; b) network size expansion.

scenarios. This requires characterization of the blocking losses. For the setup in Fig. 3c, the blocking region characteristics are shown in Fig. 3d. It is clear that the intermediate node can cause significant blocking loss. Interestingly, there lies an intermediate region between the blocking and nonblocking region, which can provide energy gain due to reflection.

RF CHARGING TIME CHARACTERIZATION

To characterize the RFET and MPER, it is necessary to characterize the capacitor charging from an RF source. A recent study [10] has shown that RF charging is different from the conventional constant voltage charging. It is a special case of constant power charging, because the RF power received for recharging the capacitor is fixed for an RF source transmitting constant power from a fixed distance. It provides the analytical expression for the time required to charge a capacitor having an initial voltage up to some threshold value depending on the energy requirement of the sensor node. Experimental validation of the RF charging equations using a Powercast P1110 EVB has also been provided. The derived charging time equation in [10, Eq. 13] as a function of received DC power P_R^{DC}, circuit parameters (capacitance and resistance), and the lower and upper voltage limits (corresponding to the initial and final charge stored in the capacitor) can be used for analyzing the RFH efficiency.

NETWORK SIZE EXPANSION: CONSEQUENCE OF MPER

We now discuss how the energy efficiency improvements provided by improved RFH techniques via MPER can provide network size expansion. Consider the network model shown in Fig. 4a, where a mobile node (called the integrated data and energy mule, or IDEM) with dedicated RF source and MPER capability has the objective of providing uninterrupted network operation by regularly visiting the nodes to recharge them and collect field data [2]. Network size can be defined as *the number of nodes that can be served by a single mobile dedicated RF source in such a way that none of the nodes ever runs out of energy*. This network size extension is achieved by quicker charging of the nodes via advanced RFH circuits (20 percent gain [5]) and RFH communication (total 30 percent gain [9]) techniques. In total, we consider an energy harvesting efficiency improvement of around 50 percent (Table 1), leading to 50 percent more received DC power. The corresponding charging time gain is obtained using [10, Eq. 13].

In [11], it was shown that the average energy consumption per sensing cycle in a node in a pollution monitoring application increases from 50–60 J to 140–150 J as the number of sensors per node is increased from one to four, which is an increment of nearly 30 J per additional sensor. The node energy consumption is a random variable because it depends on the pollution level. Thus, the network size depends on the average charging time, which in turn depends on the average energy consumption per node. In order to serve the maximum number of nodes, the IDEM should spend the minimum time traveling so that the length of the overall tour is minimized.

We have considered sensor nodes that are uniformly randomly deployed over a square field of 5 km × 5 km. The IDEM speed is assumed to be 5 m/s. The charging time parameters, based on the experimental observations, are: charging distance $d = 0.328$ m; RF transmit power = 3 W; operating frequency = 915 MHz; transmitter and receiver antenna gains of 6 dBi; capacitor value $C = 20$ F with ESR $R = 0.16\ \Omega$. For simplicity, we have considered that each node will be visited only once in a cycle. Hence, the IDEM should follow the shortest

S. No.	Strategy		Gain (%)	Challenges	Opportunities
1	**Improved RFH circuit design**		20–30% [5, 7]	Low efficiency for very low RF inputs; Hardware constraints; Supporting wide-band and multi-band operation	It plays the central and most significant role; can provide efficient ambient RFH; bridges the gap between data and energy sensitivity of receiver; scalable rectenna array
2	**Multipath energy routing (MPER)**	(a) MPER in sparse networks	10–20%	Lower efficiency due to lower transmit power of the relay; Cost of deploying dummy nodes	Can provide RFET range extension, if single-hop energy cannot be received due to path loss and lower receiver sensitivity
		(b) MPER in dense networks	10–30%	Lower inter-node distances; Node deployment not suitable to higher order MHET	Improves RFH efficiency by simultaneous charging of multiple nodes, MHET by using the nodes causing blocking of DET as energy routers
3	**Relay node optimizations**	(a) Optimal relay placement	5–10% [9]	Non-convex Optimization problem	Effectiveness of MPER and MHET is strongly affected by relay placement
		(b) Cooperative relaying [15]	Not quantified	Relay selection has to solve non-trivial reliable data-efficient energy transfer trade-off due to huge discrepancy in data and energy reception sensitivity	Can boost harvesting efficiency, meet QoS requirements by using relay nodes by exploiting the beamforming and diversity gains
4	**Beamforming**	(a) Distributed beamforming [13]	Not quantified	Overhead cost involved in the phase and frequency synchronization of the carrier signals generated by the local oscillators of differently located RF energy transmitters	Significant RFH efficiency improvement by cooperative transmission of distributed and independent transmitters; sophisticated digital implementation of optimal frequency and phase estimator instead of analog phase locked loop can further increase efficiency
		(b) Energy beamforming [1]	Not quantified	Nontrivial tradeoffs in allocating communication resources for optimizing interference levels and RFH efficiency; Form factor constraints	Energy allocation based on estimated CSI can provide a higher harvesting efficiency via energy beamforming
5	**Protocol-based optimizations**	(a) MAC	>100% [14]	Optimal energy transfer v/s data communication trade-off	Integration among efficient energy harvesting, multi-antenna transmission, data communication, resource management, and signal processing
		(b) Routing	Yet to study	Joint optimization of RFH and networking parameters; Factors like low receiver sensitivity, propagation losses, judicious utilization of the nearby sensor nodes (energy routers), varying residual energy at different nodes	Optimal joint routing and recharging scheme for mobile dedicated RF source(s) can lead toward uninterrupted network operation [2]

Table 1. Strategies for improving RFH efficiency.

Hamiltonian cycle, which has been found by solving the Traveling Salesman Problem using a genetic algorithm.

The simulation results are based on an average of 30 runs. The percentage improvement in charging time and network size achieved due to the implementation of RFH communication techniques is shown in Fig. 4b for all four cases. The results show that on average, there is about 35 percent reduction in charging time of the nodes and about 50 percent increase in the number of nodes than can be served by a single IDEM. Thus, RFH efficiency improvement can not only prolong the network lifetime but also provide network expansion.

THEORETICAL ADVANCES ON RFH COMMUNICATIONS

We now discuss the recent developments on RFH communication that are primarily theoretically driven. These include novel methods at the physical layer as well as the upper communication layers.

MULTIPLE ANTENNA TRANSMISSION

Single-antenna transmitters with omnidirectional radiation cause significant path loss with increasing transmission distance due to beam spreading. Multi-antenna transmission can achieve spatial multiplexing as in multiple-input multiple-output (MIMO) systems, by employing beamforming techniques (Fig. 5) to improve the RFH efficiency in long-distance energy transfer by exploiting large antenna array gain. This enables faster charging without any increase in transmit power. This RFET method of concentrating the RF waves in the direction of the intended receiver is called energy beamforming, which was first considered in [1] for SWIPT in multiuser downlink.

An issue associated with beamforming gains is channel state information (CSI) feedback. In [12], it was shown that energy beamforming based on accurate CSI feedback can provide higher energy transfer efficiency. However, this is at the cost of significant time overhead incurred at the receiver. A longer channel estimation duration can provide a

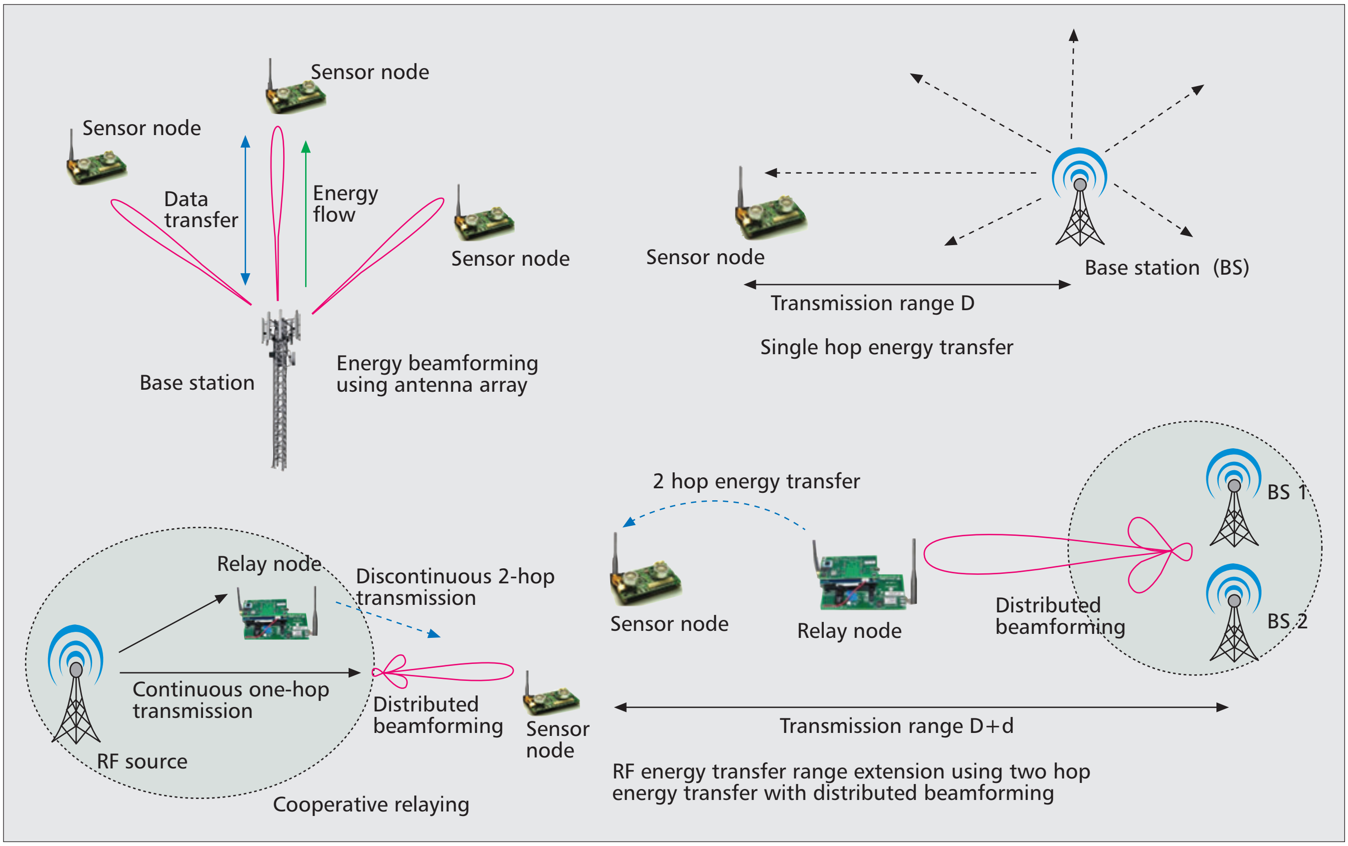


Figure 5. Beamforming techniques for the enhancement of RF harvesting efficiency.

more accurate CSI, but it also shortens the energy transfer duration, which leads to less harvested energy.

DISTRIBUTED BEAMFORMING OF MULTIPLE TRANSMITTERS

A fully wireless distributed beamforming prototype based on a software defined radio platform was proposed in [13], where several nodes finetune their data transmissions in a coordinated fashion so as to form a large virtual antenna array that directs the beam toward the receiver, thereby increasing the data rate and transmission range. Frequency and phase synchronizations were made using receiver feedback packet waveform and payload using extended Kalman filtering and a 1-bit feedback algorithm, respectively, which is an overhead cost. Along similar lines, collaborative beamforming of distributed RF energy transmitters can provide improved energy efficiency due to increased received power [14]. Cooperative beamforming has the potential to enhance energy efficiency by adjusting the carrier phase of each energy transmitter in such a manner that it can compensate for the path difference between the energy waves arriving at the target node, causing constructive interference. As a result, there can be a maximum of N^2 times power reception of RF power for N cooperative RF energy transmitters due to the increased directivity. Figure 5 shows that cooperative distributed beamforming can provide range extension, which can be further aided by 2-hop RFET. However, the major underlying challenge is the overhead cost required for frequency, phase, and time synchronization for high-frequency carrier signals.

COOPERATIVE RELAYING

Selection of a relay node among various relays strongly affects the performance of cooperative relaying that can provide improved energy transfer efficiency and better data transfer reliability. In [15] a stochastic-scale geometry approach has been adopted to study the impact of cooperative density and relay selection to analyze the fundamental trade-off between information transfer efficiency in terms of outage probability performance and RFH efficiency in SWIPT applications. But the author's objective of SWIPT to the same node is a very challenging task because of very different sensitivities to data and energy reception process. Cooperative energy relaying is useful in RFET, when the inter-nodal distances are small. Here, the end node can simultaneously receive from both the RF source and the relay node(s), which is conceptually similar to MPER. In fact, the energy gains can be further increased by distributed beamforming of continuous transmission of the RF source and the discontinuous transmission of relay nodes, as shown in Fig. 5.

PROTOCOL BASED OPTIMIZATION

In [14] RFH is posed as a Medium Access Control (MAC) objective to maximize the RF energy transfer rate while minimizing interference to data communication. The proposed RF-MAC protocol tackled several challenges, namely time of energy transfer, priority between data and energy transfer, multiple transmitter charging and choice of frequency for transmission. Categorization of different energy transmitters into two groups with varying transmission frequencies based on their phase differences, helped improve the RFH efficiency. It was shown that the RF-MAC protocol maintains a balance between the efficient RFH and data transfer by outperforming the classical modified carrier sense multiple access (CSMA) protocol in terms of both average harvested RF energy and the average network throughput.

THE WAY FORWARD: RESEARCH CHALLENGES

Under the prism of the strategies discussed so far for implementing efficient RFH communication, we now discuss the challenges that lie ahead in the practical implementation of these techniques and their further extensions. These strategies are summarized in Table 1, indicating the corresponding gains (wherever available), the challenges in their implementation, and the opportunities associated with them.

Circuits and hardware constraints: RFH circuits suffering from quiescent losses at input RF power levels below –20 dBm is a limiting factor to ambient RFH and the practical implementation of SWIPT. Thus, there is an urgent need to narrow the gap between the receiver sensitivities for data and energy. With the advanced ultra-low-power electronics and custom circuits for ultra-low-power RF scavenging, it is possible to overcome this limitation in the future by integrating improved hardware with scalable approaches as in [8].

Optimizations on MPER: Energy gains provided by MPER can be improved significantly by relay node optimizations, like selecting the relay node's position, transmit power, capacitor size, optimal store and forward energy duration as decided by the charging and discharging levels, and so on. Furthermore, the optimal relay placement on a Euclidean 2D plane in a sparse network (no blocking of DET) is a nonconvex and highly nonlinear optimization problem. The problem in the dense deployment case is even more challenging, as it includes the blocking characterization of the relay node. Thus, it has to tackle the trade-off among blocking loss, reflection gain, and path loss. These formulations are some of our ongoing research.

Constraints on joint energy and data transfer: Although it has been assumed that the receiver is able to harvest energy and decode information simultaneously from the same RF signal, it is not feasible over practical data communication ranges. Hence, two practical approaches, time switching and power splitting, have been proposed in [1] for implementation of SWIPT. However, in spite of several virtues of cooperative relaying (cooperative diversity, efficient energy, and reliable data transfer), due to the huge discrepancy in the receiver's data and energy sensitivities, utilizing these assets for SWIPT is still an open issue. Also, as accurate CSI estimation can significantly affect both information and energy transfer efficiency, a key challenge is to balance time resources for channel estimation and SWIPT in multi-user MIMO systems. Distributed beamforming can overcome the form factor constraints of energy beamforming or conventional MIMO by forming a virtual MIMO or antenna array system, and provide benefits like increased directivity and spectral efficiency, and enhanced spatial diversity. However, there are underlying synchronization bottlenecks, which is an open research area.

Protocol-level challenges: As far as protocol-based optimization is concerned, there is a need to consider the practical limitations discussed above. To this end, the most important challenge is to have a protocol architecture (MAC+Routing) that jointly optimizes efficient energy transfer and reliable data transfer while taking into account various parameters. Some of the critical parameters of interest are relay node placement for efficient MPER, RF charging time characterization, cooperation among the participating nodes for data and energy transfer, interference minimization, and collaborative transmission of multiple transmitters.

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CONCLUDING REMARKS

This article has explored various communication strategies that can complement RFH hardware advances toward the realization of energy harvesting communication networks. The outlined experience on hardware implementation of MPER has revealed that while the energy routing concept is practically realizable and efficient, the energy transfer range is still low. While some concepts, such as ambient RFH-driven communication and joint energy and data transfer, may have to wait due to the significant asymmetry in energy and data transfer ranges with present-day technologies, future strategies, such as multi-antenna transmission, distributed beamforming, cooperative relaying, RF-MAC, and routing optimizations, are a few promising beacons to extend the benefits of RFH. Physical challenges include time, phase, and frequency synchronization of the independent transmitters for achieving beamforming gain. Likewise, there are challenges to the upper layer strategies, which have been summarized in Table 1. By overcoming these challenges, the combined effect of these strategies can make RFH-assisted network communication a popular technology.

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BIOGRAPHIES

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