

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 on the actual feasibility of RFH communications, new research directions, and the obstacles to their practical implementation.

Index Terms—RF energy harvesting; multihop RF energy transfer; multipath energy routing; optimal relay placement; distributed beamforming; cooperative relaying

I. INTRODUCTION

In recent times, radio frequency (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; the radio waves can simultaneously carry information and energy, and the radiation directivity can be electronically steerable. These features have been exploited in Multi-Hop 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 upon 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 $P_R^{DC} = \left(\eta_{RF-DC}\right) P_R$, where P_R is the received RF power that can be calculated using the Friis transmission equation.

RF energy sources can be categorized into two categories:

- *Ambient RF*: Ambient RF energy sources are not actually dedicated for RF Energy Transfer (RFET); 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, etc.
- *Dedicated RF*: This on-demand supply generally has a relatively higher power density due to directional transmission, and it is used to recharge the nodes that require predictable and high amount of energy. The energy transfer is done in the license-free 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 it has the 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 on 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 as compared to wireless data transfer because the information reception sensitivity is higher by a few orders of magnitude (typically -60 dBm in data reception versus -10 dBm in RFH). This implies that, with the current state of devices and RF circuits technologies, some of the applications may have limited practical utility. For example, the wireless energy plus 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 a meter.

The first goal of this article is to provide an overview of the recent developments toward improving RF energy harvesting efficiency. Some novel approaches that we will discuss include increasing RF energy harvesting 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.

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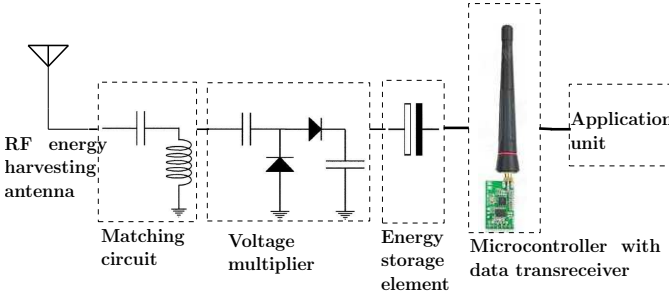


Fig. 1: RF energy harvesting node.

II. IMPROVED RFH CIRCUITS

The general architecture of a RFH unit is shown in Fig.1. The harvested energy is used to run a low-power microcontroller 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.

A. 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 of multiple stages of parallel capacitors is used for a high RF-to-DC conversion efficiency [5].

Because of the non-linearity 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 the low input RF power and the other with ten stages for a higher input RF power – was proposed in [5] and an optimization framework was used to decide on the switch over point between the two stages, resulting in about 20% 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.

B. 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, it has been suggested to insert 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. Also, it has also 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.

III. EXPERIMENTAL INSIGHT ON SMART RFH COMMUNICATIONS

As noted in Sections I and II, 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) that provides an efficient RFH communication by overcoming these hardware based shortcomings. MPER helps in improving the 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 alternate paths other than the direct single hop path (Fig. 2). These 'energy routers' can be part of the network or may be introduced as optimally positioned dummy nodes. MPER is based on the principle that Multi-Hop Energy Transfer (MHET) is beneficial to the energy transfer process.

MHET can improve the 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. By 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.

A. MPER in a sparse deployment scenario

In a sparse deployment, the intermediate nodes' presence do 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

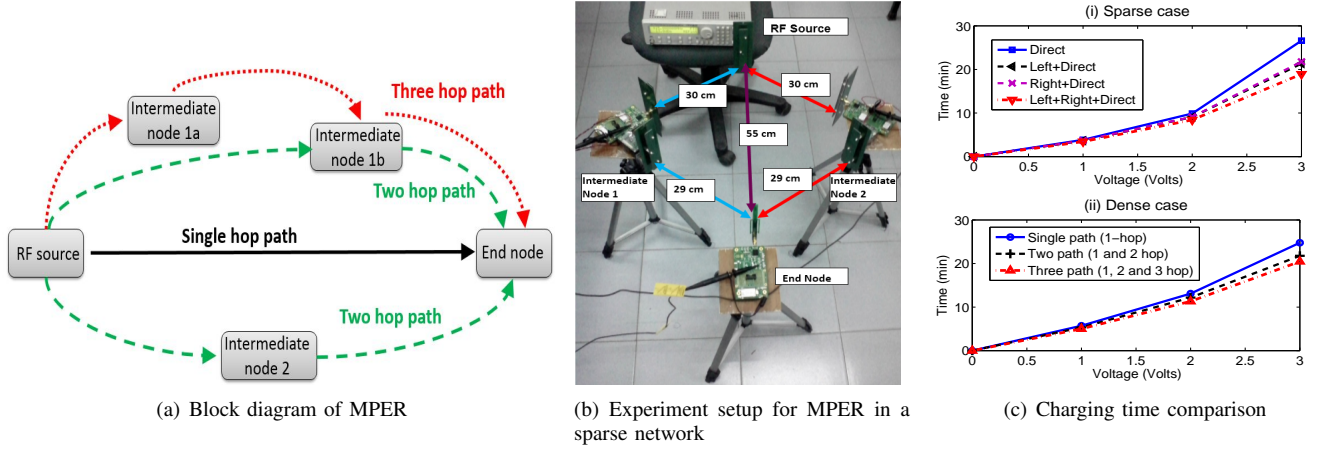


Fig. 2: Multipath energy routing.

shown in Fig. 2, where for improving gain, two intermediate nodes are symmetrically placed on the either sides of the LOS path – constituting a 3-path energy transfer.

The system specifications for the experimental set-up are: HAMEG RF synthesizer transmitting +13 dBm at 915 MHz via 6 dBi Powercast patch antenna; intermediate nodes composed of Powercast P1110 EVB, Mica2 mote, two Powercast 6 dBi patch antennas; end node comprised of Powercast P1110 EVB, Powercast 1 dBi dipole antenna. Further details related to the experimental set-up 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 2-path scenarios (left+direct, right+direct) as well as in the 3-path scenario (direct+left+right) are shown in Fig. 2(c.i). Compared to DET, time saving to charge the end node's capacitor up to 3 V is about 18% and 28%, respectively, in the 2-path and 3-path cases. The energy gain is the same as the time gain, as energy and time are proportional for a constant power source.

B. MPER in a dense deployment scenario

In a dense deployment, charging of one sensor node directly using LOS RF energy transmission may not be very efficient because of blocking/shadowing caused by the neighboring nodes. So, 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 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 3-hop energy transfer. Referring to Fig. 2(a), the intermediate nodes present are 'node 1a' and 'node 1b'. In the 2-hop path, 'node 1a' does not participate in RFET.

The representative results as plotted in Fig. 2(c.ii) show that both 2-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%, respectively, over DET for charging the end node up to 3 V.

C. Optimal relay placement

As demonstrated in Sections III-A and III-B, 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 3 cases in a 2-hop RFET (Fig. 3(c)) 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:* Relay node is closer to the RF source, and so it harvests energy at a faster rate and forwards energy more frequently (with more number of on/off cycles, see Fig. 3(a)). However, the energy received per cycle at the end node is very low due to a higher path loss.
- *Case B:* Relay node is at the midway point to the end node. It harvests a lesser amount of energy as compared to case A over a given time. Also, the energy received per forwarding cycle by end node is lesser than case C due to higher path loss.
- *Case C:* 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. 3(b). The average energy gain was noted to be about 10% over the worst case [9].

The above experimental study, however, calls for optimization formulations to find the optimum intermediate node posi-

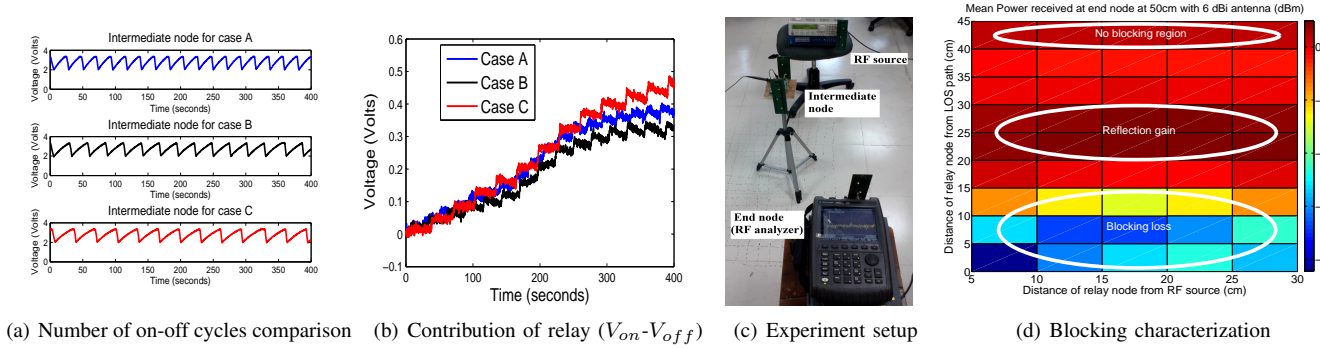


Fig. 3: Effect of intermediate node placement.

tions to maximize RFET efficiency under different deployment scenarios. This requires characterization of the blocking losses. For the setup in Fig. 3(c), the blocking region characteristics are shown in Fig. 3(d). 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.

D. RF charging time characterization

To characterize the RFET and MPER, it is required to characterize the capacitor charging from a 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 a 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 upon the energy requirement of the sensor node. Experimental validation of the RF charging equations using Powercast P1110 EVB has also been provided. The derived charging time equation in [10, equation (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.

E. 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. 4(a), where a mobile node (called Integrated Data and Energy Mule, or IDEM) with dedicated RF source and MPER capability has the objective to provide uninterrupted network operation by regularly visiting the nodes for recharging them and collecting 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 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% gain [5]) and RFH communication (total 30% gain [9]) techniques. In total, we consider an energy harvesting

efficiency improvement of around 50% (cf. Table I), leading to 50% more received DC power. The corresponding charging time gain is obtained using [10, equation 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 1 to 4, which is an increment of nearly 30 J per additional sensor. Energy consumption of the node is a random variable because it depends on the pollution level. So, the network size depends on the average charging time, which in turn depends on the average energy consumption per node. In order to serve maximum number of nodes, the IDEM should spend minimum time in 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 \times 5 km. The IDEM speed is assumed to be 5 m/s. The charging time parameters, taken based on the experimental observations, are: charging distance $d = 0.328$ m; RF transmit power is 3 W; operating frequency = 915 MHz; the transmitter and receiver antenna gains are 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. So, the IDEM should follow the shortest Hamiltonian cycle, which has been found by solving the Traveling Salesman Problem using Genetic Algorithm.

The simulation results are based on the 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. 4(b) for all four cases. The results show that, on average, there is about 35% reduction in charging time of the nodes and about 50% increase in the number of nodes than that can be served by a single IDEM. Thus, RFH efficiency improvement can not only prolong the network lifetime but can also provide network expansion.

IV. 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.

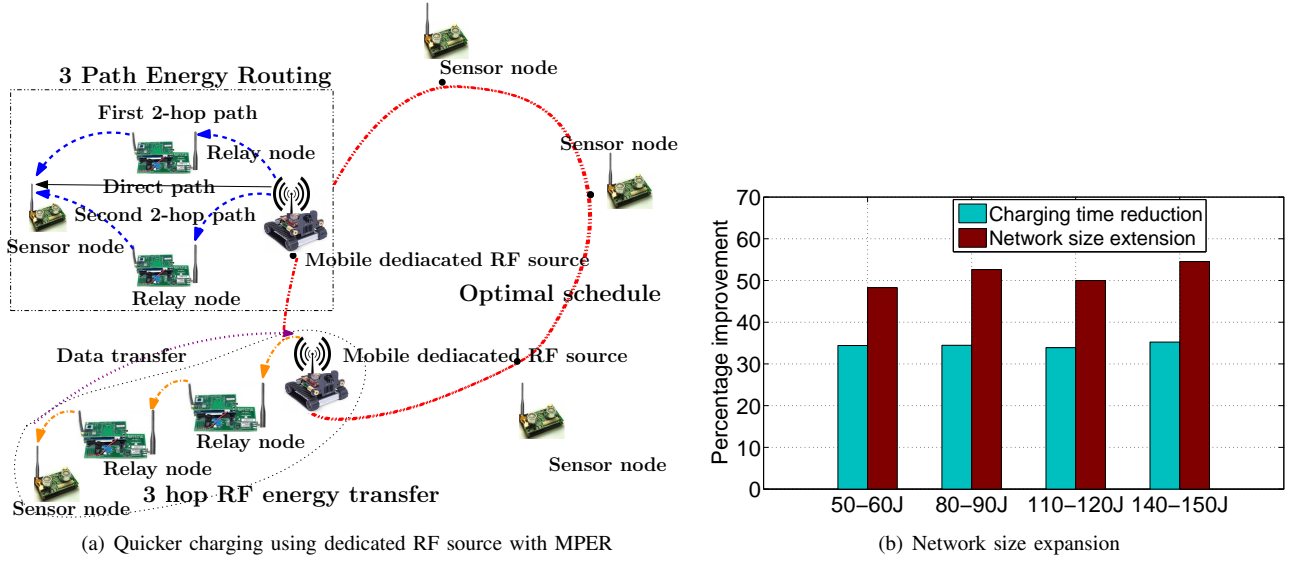


Fig. 4: Networking consequence of improved RFH efficiency.

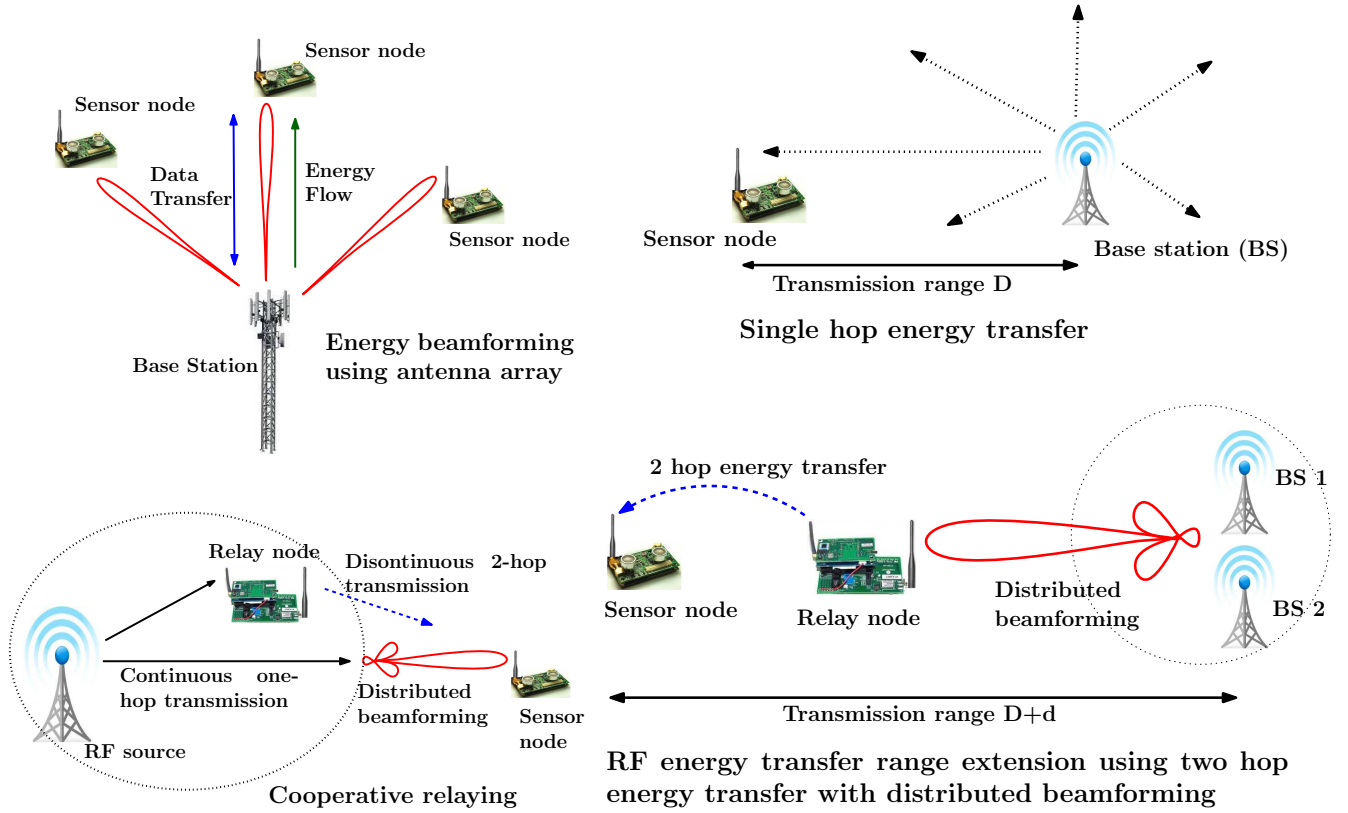


Fig. 5: Beamforming techniques for the enhancement of RF harvesting efficiency.

A. Multiple antenna transmission

Single-antenna transmitters with omni-directional 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 a 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 more accurate CSI, but it also shortens the energy transfer duration, which leads to a less harvested energy.

B. 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 fine-tune their data transmissions in a coordinated fashion so as to form a large virtual antenna array, that directs the beam towards 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 one 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 of enhancing 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. Fig. 5 shows that cooperative distributed beamforming can provide range extension, which can be further aided by two hop RFET. However, the major underlying challenge is the overhead cost required for the frequency, phase and time synchronization for high frequency carrier signals.

C. 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.

D. 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 in improving 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 Medium Access (CSMA) protocol in terms of both average harvested RF energy and the average network throughput.

V. 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 I, indicating the corresponding gains (wherever available), 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, etc. Further, the optimal relay placement on a Euclidean 2-D 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. So, two practical approaches – time switching and power splitting, have been proposed in [1] for implementation of SWIPT. Yet, in spite of several virtues of cooperative relaying, namely, 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. Further, 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

TABLE I: Strategies for improving RFH efficiency

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; Bridging the gap between data and energy sensitivity of receiver; Scalable rectenna array [8]
2	Multipath energy routing (MPER)	(a) MPER in sparse networks	10-20 % (Section III-A)	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 % (Section III-B)	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 towards uninterrupted network operation [2]

constraints of energy beamforming or conventional MIMO by forming a virtual MIMO or antenna array system, and provide benefits like increased directivity, 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 as discussed above. To this end, the most important challenge is to have a protocol architecture (MAC+Routing) that jointly optimizes the 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.

VI. CONCLUDING REMARKS

This article 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 current day technologies, the 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 I. By overcoming these challenges, the combined effect of these strategies can make RFH-assisted network communication a popular technology.

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REFERENCES

- [1] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.
- [2] S. De and R. Singhal, “Toward uninterrupted operation of wireless sensor networks,” *IEEE Computer Mag.*, vol. 45, no. 9, pp. 24–30, Sep. 2012.
- [3] N. Shinohara, *Wireless Power Transfer via Radiowaves*. Hoboken, NJ, USA: Wiley, 2014.
- [4] A. Kurs, A. Karalis, R. Moffatt, J. Joannopoulos, P. Fisher, and M. Soljacic, “Wireless power transfer via strongly coupled magnetic resonances,” *Science*, vol. 317, no. 5834, pp. 83–86, July 2007.
- [5] P. Nintanavongsa, U. Muncuk, D. Lewis, and K. Chowdhury, “Design optimization and implementation for RF energy harvesting circuits,” *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 2, no. 1, pp. 24–33, Mar. 2012.
- [6] Powercast. [Online]. Available: <http://www.powercastco.com>.
- [7] S. Agrawal, S. Pandey, J. Singh, and M. Parihar, “Realization of efficient RF energy harvesting circuits employing different matching technique,” in *Proc. Int. Symp. Quality Electronic Design*, Santa Clara, CA, USA, Mar. 2014, pp. 754–761.

- [8] Z. Popovic, S. Korhummel, S. Dunbar, R. Scheeler, A. Dolgov, R. Zane, E. Falkenstein, and J. Hagerty, "Scalable RF Energy Harvesting," *IEEE Trans. Microw. Theory Tech.*, vol. 62, no. 4, pp. 1046–1056, Apr. 2014.
- [9] K. Kaushik, D. Mishra, S. De, S. Basagni, W. Heinzelman, K. Chowdhury, and S. Jana, "Experimental demonstration of multi-hop RF energy transfer," in *IEEE 24th Int. Symp. on Personal Indoor and Mobile Radio Communications (PIMRC)*, London, UK, Sep. 2013, pp. 538–542.
- [10] D. Mishra, S. De, and K. R. Chowdhury, "Charging time characterization for wireless rf energy transfer," *IEEE Trans. Circuits Syst. II*, to be published.
- [11] P. Gupta, K. Kandakatla, S. De, and S. Jana, "Feasibility analysis on integrated recharging and data collection in pollution sensor networks," in *Proc. Nat. Conf. Commun. (NCC)*, New Delhi, India, Feb. 2013.
- [12] G. Yang, C. K. Ho, and Y. L. Guan, "Dynamic resource allocation for multiple-antenna wireless power transfer," *IEEE Trans. Signal Process.*, vol. 62, no. 14, pp. 3565–3577, July 2014.
- [13] F. Quitin, M. M. U. Rahman, R. Mudumbai, and U. Madhow, "A scalable architecture for distributed transmit beamforming with commodity radios: Design and proof of concept," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1418–1428, Mar. 2013.
- [14] M. Naderi, P. Nintanavongsa, and K. Chowdhury, "RF-MAC: A medium access control protocol for re-chargeable sensor networks powered by wireless energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3926–3937, July 2014.
- [15] I. Krikidis, "Simultaneous information and energy transfer in large-scale networks with/without relaying," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 900–912, Mar. 2014.

VII. BIOGRAPHIES

DEEPAK MISHRA [S'13] received his B.Tech degree in Electronics and Communication Engineering from Guru Gobind Singh Indraprastha University, Delhi, India, in 2012. He is currently pursuing the Ph.D. degree from the Department of Electrical Engineering, IIT Delhi, India. His research interests include energy harvesting, wireless rechargeable sensor networks and mobility management in ad hoc sensor networks.

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STEFANO BASAGNI holds a Ph.D. in electrical engineering from the University of Texas at Dallas (December 2001) and a Ph.D. in computer science from the University of Milano, Italy (May 1998). Since 2002 he is an associate professor at the Department of Electrical and Computer Engineering at Northeastern University, in Boston, MA. Dr. Basagni's current research interests concern research and implementation

aspects of mobile networks and wireless communications systems, radio and acoustic sensor networking, definition and performance evaluation of network protocols and theoretical and practical aspects of distributed algorithms. Dr. Basagni has published over six dozens of refereed technical papers and book chapters that are highly cited (his h-index is currently 29, with over 7500 citations to his works). He is also co-editor of three books. Dr. Basagni serves as a member of the editorial board and of the technical program committee of ACM and IEEE journals and international conferences. He is a senior member of the ACM (including the ACM SIGMOBILE), a senior member of the IEEE (Computer and Communication societies), a member of ASEE (American Society for Engineering Education) and of CUR (Council on Undergraduate Research).

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WENDI HEINZELMAN is a Professor in the Department of Electrical and Computer Engineering at the University of Rochester, with a secondary appointment in the Computer Science Department at Rochester. She also currently serves as the Dean of Graduate Studies for Arts, Sciences & Engineering. Dr. Heinzelman received a B.S. degree in Electrical Engineering from Cornell University in 1995 and M.S. and Ph.D. degrees in Electrical Engineering and Computer Science from MIT in 1997 and 2000, respectively. Her current research interests lie in the area of wireless communications and networking, mobile computing, and multimedia communication. Dr. Heinzelman is currently an Associate Editor for Elsevier Ad Hoc Networks and Information Director for ACM Transactions on Sensor Networks. She is a member of Networking Networking Women (N² Women) and the Society of Women Engineers (SWE), a Distinguished Scientist of ACM Sigmobile, and a Senior Member of the IEEE Communications Society and the IEEE Signal Processing Society.

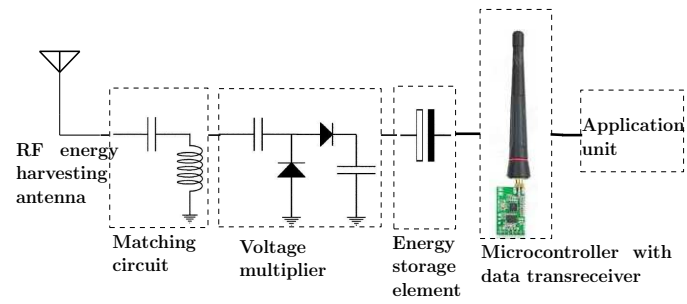


Fig. 1: RF energy harvesting node.

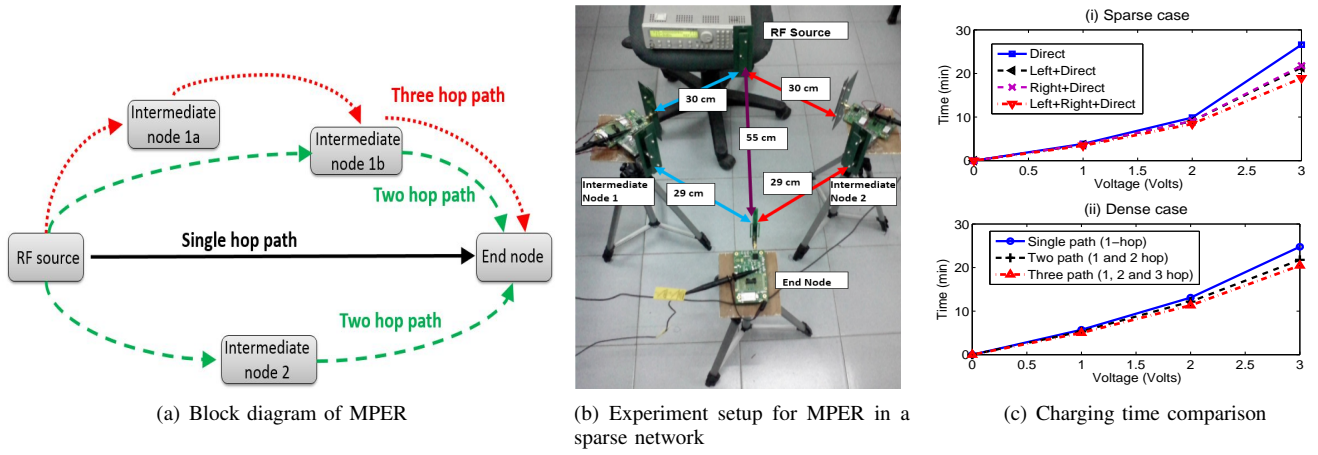


Fig. 2: Multipath energy routing.

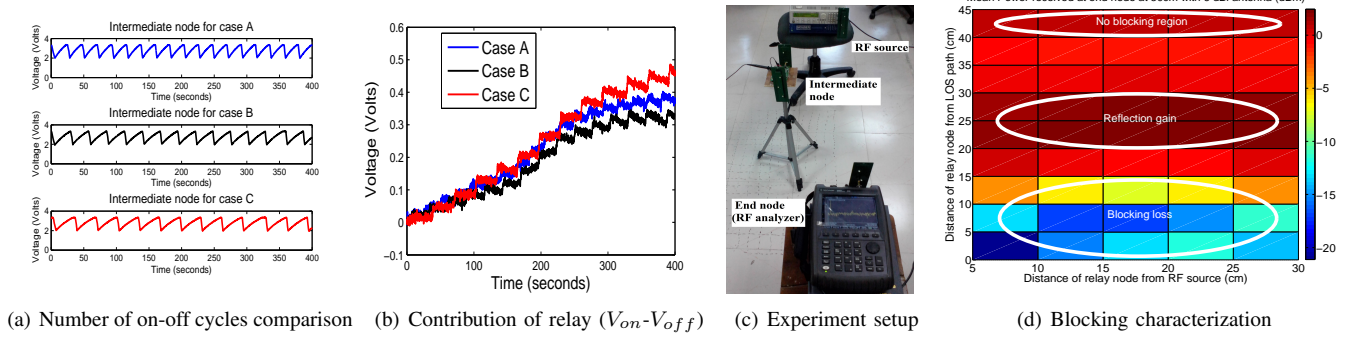


Fig. 3: Effect of intermediate node placement.

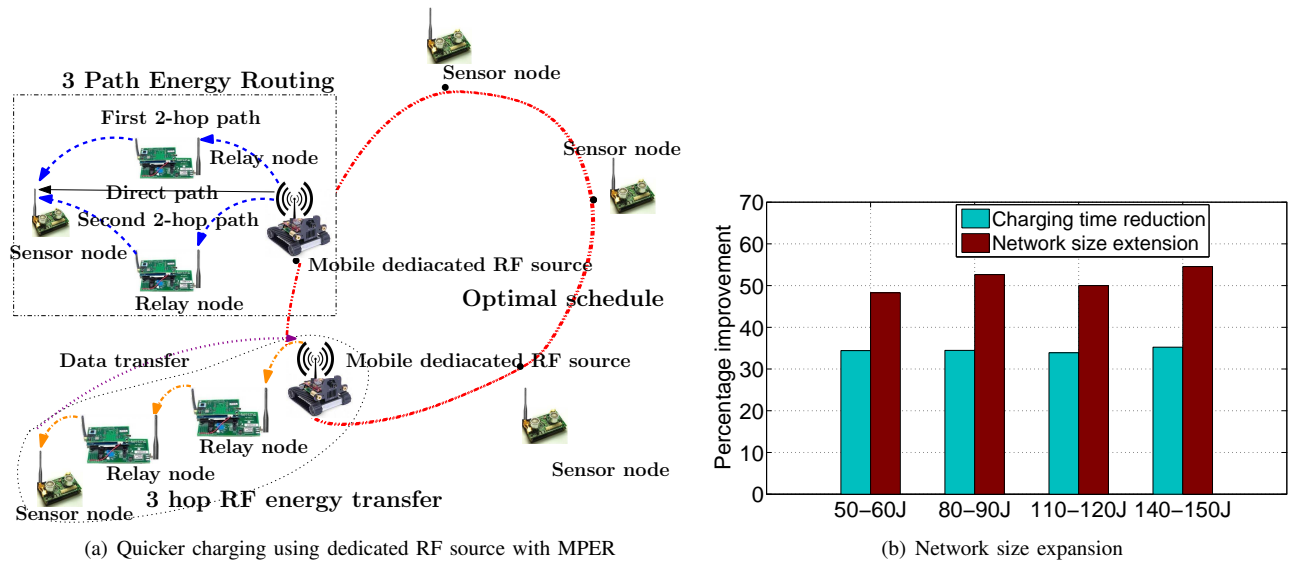


Fig. 4: Networking consequence of improved RFH efficiency.

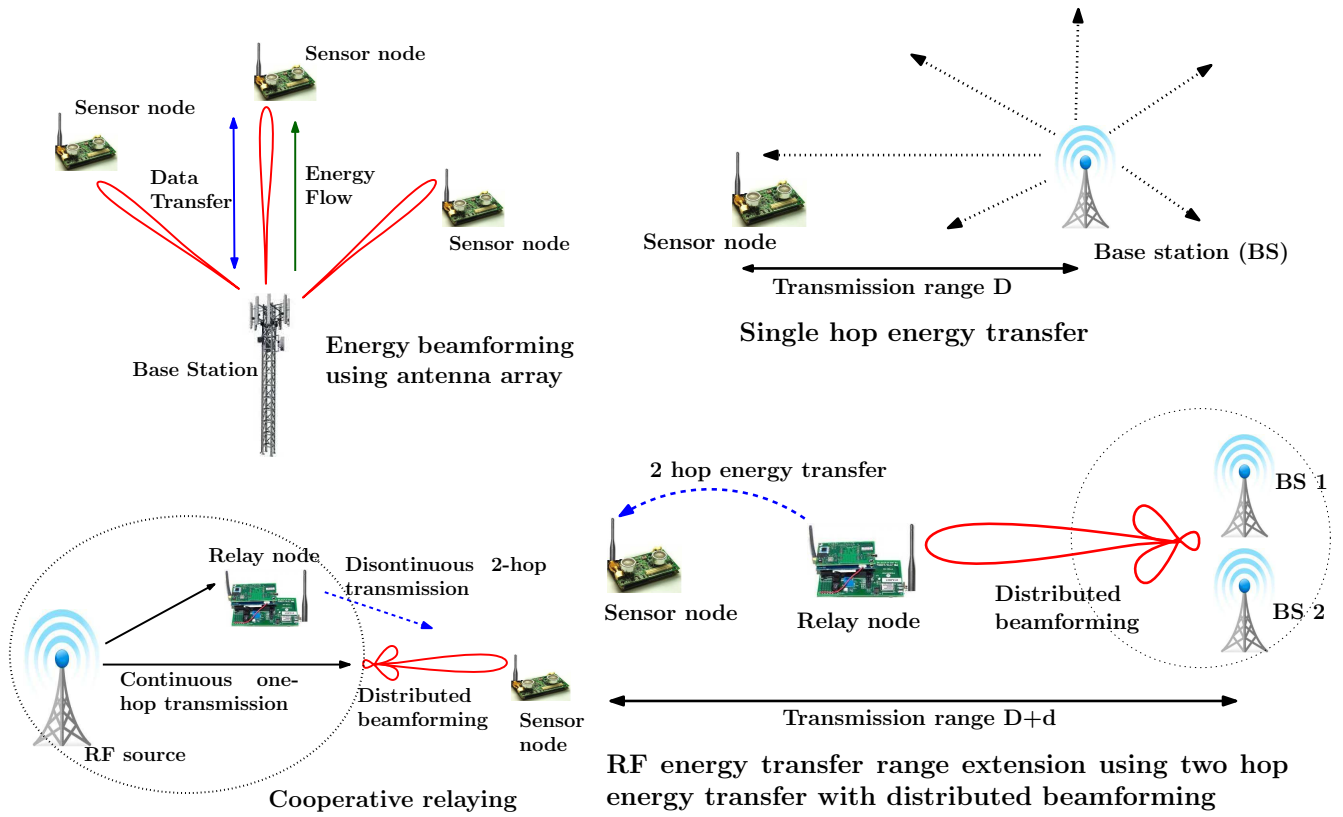


Fig. 5: Beamforming techniques to enhance RF harvesting efficiency.

TABLE I: Strategies for improving RFH efficiency

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; Bridging the gap between data and energy sensitivity of receiver; Scalable rectenna array [8]
2	Multipath energy routing (MPER)	(a) MPER in sparse networks	10-20 % (Section III-A)	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 % (Section III-B)	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 towards uninterrupted network operation [2]