Towards Uninterrupted Operation of Wireless Sensor Networks

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Abstract

A common challenge in wireless sensor networks is the limited energy resource of field nodes. One way to recharge them is to use the radio frequency (RF) energy that could be available in-network or transmitted from a wireless station. This article outlines the possibility of nonstop network operation by introducing a two-step energy transfer and data collection process with the help of a mobile agent that can act as a data sink as well as wireless energy source. To reduce the complexity of operation, a dense network can be clustered based on the energy sensitivity of the wireless nodes. To increase energy efficiency, the RF energy transfer is done over multiple hops while the field data are collected in single-hop. Via numerical and experimental studies it is demonstrated that, under certain optimum distance conditions multi-hop energy transfer is efficient in terms of energy and time. The energy and data transfer protocols are also outlined. This feasibility study is expected to pave green ways to recharging and uninterrupted operation of the field sensor nodes.

Index Terms

Uninterrupted network operation, multi-hop RF energy transfer, mobile agent, clustered topology

I. INTRODUCTION

With the rapid advancement of low-power microelectronics, the concepts of connecting the physical world via networked sensors are being actively pursued in the networking research community. There are plenty of potential military and civilian applications of single-hop/multi-hop ad hoc sensor networks, each associated with its individual uniqueness. Telemetric applications, such as monitoring of structural health, field crop growth, hazardous factory floor, weather pollution, medical health care, etc., are to name a few. However, a key bottleneck to widespread use of sensor networks in all these applications has been the cost of maintenance network-capable sensor nodes due to their limited battery life. Although the energy efficient communication protocols try to ensure extended network lifetime, network disconnection problem due to battery drainage is still a major challenge.

In many applications, due to deployment terrain condition or because of the sheer number of field nodes, it is not cost-feasible to replace the exhausted batteries without interrupting the network operation. To this end, wirelessly recharging of nodes from dedicated sources or peer nodes is an interesting solution. One approach that serves well the purpose of network lifetime extension is energy harvesting – a process by which energy is derived from external ambient sources. While there have been proposals on tapping the non-network ambient energy sources, such as vibrations [1], wind [2], thermal gradient and strain from human activities [3], ambient RF (radio frequency) [4], solar [5], etc., as well as a combination of them [6], such resources are not universally available. As a result, such ambient energy sources are not reliable for uninterrupted network operation.

A. *State-of-the-Art on Wireless Energy Transfer*

Recharging from dedicated electrical sources are being investigated at the research level [7] as well as explored commercially. eCoupled Technology (ecoupled.com) provides a wireless energy transfer method using electromagnetic induction. WildCharge Technology (wildcharge.com) requires the surface contact between transmitter and receiver. A radiative approach by Powercast Technology (powercastco.com) provides wireless power on demand or as scheduled, without requiring a surface contact between transmitter and receiver, where additional RF-to-DC (direct current) rectification circuitry is required at the receiver that are available commercially. WiTricity (witricity.com) is a non-radiative method which uses resonant electromagnetic coupling to transfer energy at mid ranges (1-3 meters). Recently, [8] explored this non-radiative energy transfer in multi-hop sensor networks, where it was shown via analysis that, for a large number of hops, a combination of store-and-forward and direct energy transfer techniques can be beneficial. This approach is constrained by the requirement of strong coupling requirement, which is especially difficult to achieve in ad hoc networks with random deployment patterns. In [9], it was demonstrated experimentally that the power transmitted to the load drops sharply if either one of the coils is detuned from resonance.

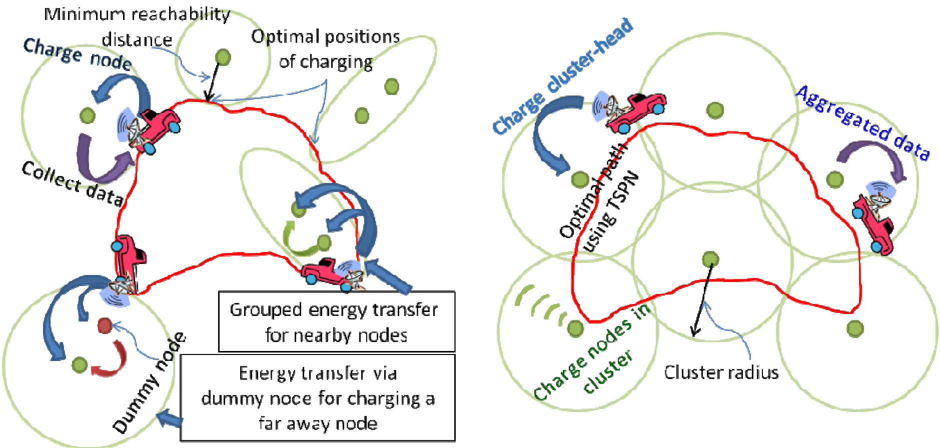
B. *Key Challenge to Uninterrupted Sensor Network Operation*

To motivate green approach to uninterrupted network operation, in Section II we outline possible sensor network architectures where the nodes rely on occasionally supplied energy from external sources, e.g., a mobile robot that can serve as an integrated data and energy MULE (IDEM), which extends that conventional data MULE concept [10]. While in principle all field nodes could be attended individually to supply energy from the external agent, a tiered approach and the possibility of multi-hop energy supply would be more practical. To this end, while the WiTricity concept could be employed, we explore the possibility of radiative energy transfer to the system's advantage in ad hoc deployment scenarios, as this approach does not have strict constraints of distance, inter-nodal alignment, and resonant coupling due to its beam (antenna radiation pattern) steering capability. Also, the radiative technique offers the possibility of charging more than one non-aligned nodes and combining energy transfer along with field data transfer over the same RF signal. It may be noted that, although multi-hop wireless communication for data transfer and its benefits have been widely studied in the literature, multi-hop RF energy transfer requires a very different outlook because of relatively very low energy sensitivity, and it has not been explored in the past. We investigate the feasibility of multi-hop RF energy transfer (ME) and how it improves the energy and time efficiency in the scenarios where single-hop RF energy transfer (SE) would have been otherwise feasible (Section III), where we also demonstrate the improvement in network operation in terms of reduced number of cluster-heads, thereby reducing the complexity of route planning of the mobile sink, and sustaining the network sensing operation for a longer time. The associated charging and data collection protocol is also outlined (Section IV).

II. COMPOSITE ENERGY SUPPLY AND DATA GATHERING NETWORK SYSTEM

We consider three cases of sensor network system where wireless energy transfer is of interest. The energy cost of network operation is critical from green communication perspective.

In a sparse network flat topology is considered. The field nodes with limited energy storage capacity are assumed to operate purely on the supplied energy from a RF energy source, e.g., an IDEM which performs the task of charging the nodes in addition to data collection from them. The IDEM's visit pattern can be either periodic or driven by the event of a node's energy availability. The field node locations can be predefined and rather static. Due to the terrain condition and the availability of physical path, appropriate charging distance of an IDEM to a node may vary. Also, dictated by the availability of physical path, it may be possible to reach more than one nodes simultaneously. Accounting these constraints, the IDEM's trajectory can be defined by suitably tuning the travelling salesman problem with neighborhood (TSPN). In this article, we will explore to increase the efficiency of energy transfer in such a network via multiple hops, as depicted in Figure 1(a).



(a)

(b)

Figure 1: Examples of energy transfer and data collection with IDEMs: (a) in flat network topology; (b) in a clustered network topology.

In a dense deployment scenario, since the number of field sensors can be potentially very large, charging and data collecting from the individual nodes would be both time consuming and complex. Instead, for scalability, they are divided into clusters with a much smaller number of cluster-heads. However, *unlike in the conventional clustering approaches in ad hoc networks, the cluster size (radius) in this case is dictated by the energy transfer capability of the cluster-head to all its cluster members*, which is a function of transmit and receive antenna gains, path loss factor, and energy sensitivity of the RF energy harvesting circuit. Energy sensitivity is defined as the minimum input power level required for successful conversion of RF-to-DC power. The cluster-heads are either solar power capable or charged by IDEMs occasionally during their data collection visits. In a clustered topology, we will look for benefits of ME over SE in terms of reduced energy consumption, increased network lifetime, and reduced number of cluster-heads.

Another potential area of exploration of benefit from ME is in wake-up radio based event-driven data communication. It was recently demonstrated in [11] that the passive wake-up radio based event-driven data collection in sensor network is far more energy efficient than its duty cucle based counterpart. However, the transmit power required for *direct* wake-up signal is quite high (1 W), and the effective wake-up communication range is also limited (4 m).

Intuitively, since a node closer to the RF source is charged quickly, the energy of a nearby node can be transferred to a distant node in a multi-hop fashion, which would help extend the cluster coverage area. Since the energy required for charging a closer node is much lesser than that for the distant nodes, there is a potential of saving energy by using ME compared to SE, which is also confirmed experimentally (Section III-B). Additionally, an energy depleted node could initiate energy transfer to itself from a neighboring peer node. Thus, ME can help not only in sustaining the network operation but also in balancing the remaining energy, thereby extending the network lifetime.

The trade-off in ME is the extra complexity in terms of high gain antennas, which can be reduced with the availability of more efficient energy harvesting circuits [12].

III. FEASIBILITY STUDIES ON MULTI-HOP WIRELESS RF ENERGY TRANSFER

To investigate the feasibility of ME approach, the field nodes are assumed to operate purely on the supplied energy from an RF energy source.

A. *Numerical Observations*

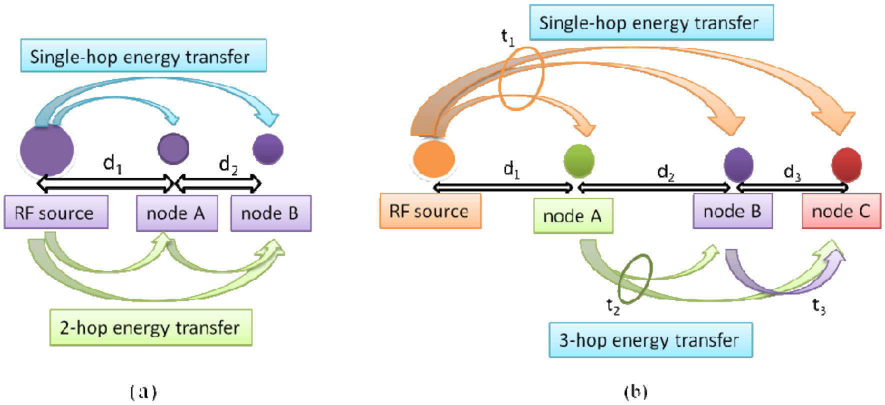


Figure 2: Examples of multi-hop energy transfer: (a) 2-hop; (b) 3-hop.

We derive in MATLAB the conditions under which ME would be beneficial. Referring to Figure 2(a), in a scenario with 3 aligned nodes, let the distance between the RF source and node A be d_1, and that between node A and another aligned node B be d_2. Operating frequency is taken as 915 MHz, RF signal path loss factor is 2.0, antenna gains are 12 dBi. For other parameters CC1000 RFIC of Mica2 (Moog Crossbow: xbow.com) and Powercast P2110 data sheets are considered: radiated power of the nodes for RF energy transfer is $P_t = +5\,\text{dBm}$; P2110 receiver energy sensitivity is $\mathrm{P_{th}} = -11.5$; both nodes A and B can be charged up to 3.3 V. For the rectification efficiency we have used Powercast P2110 datasheet (powercastco.com/PDF/P2110-datasheet.pdf).

Based on the rectification efficiency of P2110, the maximum distance between the RF source and a receiver node corresponds to a receive power $P_r \geq -11.5$ dBm. Hence, with a transmit power $P_t = +5\,\text{dBm}$, for an appreciable energy transfer from the RF source to node B, $d = d_1 + d_2 \leq d^{(\max)} = 2.76$ m. Likewise, from node A to B, at $P_t = +5\,\text{dBm}$, $d_2^{(\max)} = 2.76$ m.

While a sensor node (Mica2) is receiving RF energy, its transceiver module in power down mode consumes $i_c^{(PD)} = 0.2$ µA at an operating voltage $V = 2.8$ V. The absolute minimum criteria for energy rectification is that, the power gained after DC conversion should be at least greater than the power consumption in power down mode, which is $i_c^{(PD)} \cdot V = 0.56$ μW. So the minimum required rectified DC power is $P_r \cdot \eta(P_r) > 0.56$ μW, where $\eta(P_r)$ is the rectification efficiency at receive power P_r. We have verified that, even at the lowest input power -11.5 dBm, the condition $P_r \cdot \eta(P_r)$ > 0.56 μW is satisfied. The following conditions are noted on RF energy transfer:

Case I:

$$2d_0 < d_1 + d_2 < d^{(\max)};\ d_0 < d_1 < d^{(\max)} - d_0; d_0 < d_2 < d_2^{(\max)}$$

where d_0 is the reference distance. Under the above conditions, when it is ensured that $P_{r(A\to B)} \geq \mathrm{P_{th}}$, ME is more energy-efficient than SE in energy transfer.

Case II:

$$d_0 + d_2^{(\max)} < d_1 + d_2 < d^{(\max)};\ d_0 < d_1 < d^{(\max)} - d_2^{(\max)};\ d_2^{(\max)} < d_2 < d^{(\max)} - d_0$$

Under the above conditions, when node A to node B distance is large so that $P_{r(A\to B)} \leq \mathrm{P_{th}}$, SE is more energy-efficient than ME in energy transfer.

Case III:

$$d^{(\max)} < d_1 + d_2;\ d^{(\max)} - d_2^{(\max)} < d_1 < d^{(\max)};\ d_0 < d_2 < d_2^{(\max)}$$

In this case, SE is not possible, as the total distance $d_1 + d_2 > d^{(\max)}$, whereas ME still works, as the conditions $d_1 < d^{(\max)}$ and $d_2 < d^{(\max)}$ are individually fulfilled. In all the other cases it is found that both SE and ME are infeasible.

Thus, as long as $d_1 + d_2 < d^{(\max)}$ and the distance of node A to node B is within $d_2^{(\max)}$, node A's energy transfer is useful to node B, and ME performs better than the SE performance.

In Case III, however, although ME is feasible, it has been found that time required for charging node B is very high. *Thus, while Case I is found to be practical where ME is more energy efficient than SE, Case III is useful for only energy transfer coverage extension.*

Figure 3(a) shows the energy saved in ME as compared to SE and is consistent with the above three cases. It can be noted that, as d_1 increases, energy saved also increases. However, the percentage gain is reduced (Figure 3(b)). This is because, as d_1 increases, RF energy consumption at the RF source also increases even more rapidly. In ME, the RF source radiates for a lesser time (say, t_{d1}) if conditions of Case I are satisfied (which also results in the overall energy saving in ME). On the other hand, the time cycle for energy transfer to node B increases by t_{d2} due to the extra time consumed when node A transfers energy to node B. Thus, if $t_{d1} > t_{d2}$, then effectively total time cycle in ME would be shorter than in SE.

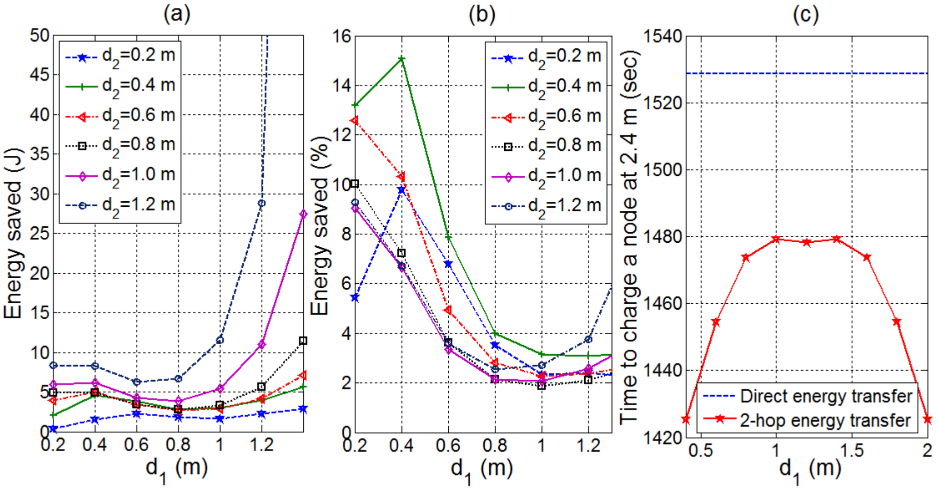


Figure 3: Energy and time saved in ME as compared to SE, as a function of $\boldsymbol{d_1}$. $\boldsymbol{d_1 + d_2 = 2.4}$ m.

To demonstrate the time saving, we compared the time required in SE and ME for the two nodes (A and B) attain the same voltage level (1 V). Figure 3(c) shows the time saved by using ME as the position of intermediate node is varied. As observed from this figure, saving is less when $\boldsymbol{d_1}$ and $\boldsymbol{d_2}$ are approximately equal. This is because, when $\boldsymbol{d_1}$ and $\boldsymbol{d_2}$ are very different, one pair of the nodes is close-by, resulting in a higher RF to DC conversion efficiency and hence saving time in charging.

In general, in an n-hop energy transfer, starting at the RF source, let the ith node radiates at transmit power P_{ti} and the corresponding maximum energy transfer distance is $d_i^{(\max)}$. The conditions for benefit of n-hop energy transfer over a k-hop transfer $(k < n)$ are:

$$d_1 + d_2 + \cdots + d_n < d_1^{(\max)};\ d_2 + d_3 + \cdots + d_n < d_2^{(\max)};\ \cdots;\ d_n < d_{n-1}^{(\max)}$$

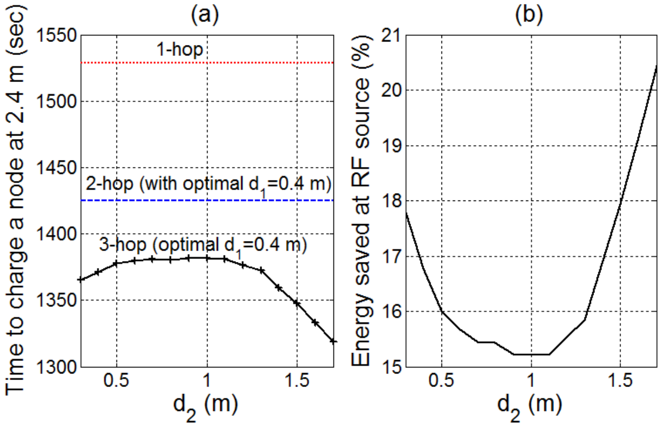


Figure 4: Performance gain in multi-hop charging: (a) time saved; (b) reduced energy consumption in 3-hop charging.

To numerically quantify the benefits of increasing the number of hops, we consider a 3-hop energy transfer scenario (Figure 2(b)). In one cycle of energy transfer, the RF source transmits energy for time t_1 when all the nodes A, B, and C harvest RF energy. Next, for time t_2 node A radiates to B and C, and for time t_3 node B radiates to C. The RF source transmits at $P_{t1} = +5$ dBm. $P_{t2} = P_{t3} = +5$ dBm. Keeping all other system parameters same as in 2-hop case, we have, $d_1^{(\max)} = d_2^{(\max)} \equiv 2.76$ m. The energy and time savings with an increased hop count are shown in Figure 4, where the total distance kept at 2.4 m. Figure 4(b) shows up to 20% energy saving in 3-hop energy transfer.

Overall, in a dense network, ME could be used for more efficient energy transfer or wake-up process. On the other hand, in a sparse network, one or more dummy nodes could be placed optimally between the RF source and the field node to benefit from ME.

To study the benefit of multihop charging, we considered P2110 RF energy harvester data sheet and a square grid deployment of cluster-heads transmitting at +5 dBm power. For ME, the intermediate nodes transmit at +5 dBm. If the cluster size is defined by the distance from a cluster-head to a furthest away cluster member that can be charged up to replenish the minimum required energy, which is 1.57 mJ for 128 Bytes data transfer per cycle, the reduction in the number of required cluster-heads to cover a sensing area is 12.77% if up to 3-hop charging is practiced. This observation further demonstrates the benefit of ME in reducing the number of cluster-heads and hence the network deployment cost as well as complexity IDEM's path planning.

B. Experimental Steps and Results

To verify the feasibility of ME we have conducted hardware experiment using Powercast P1110 RF energy harvesting kit operating at 915 MHz band and with energy sensitivity of -5 dBm. The antenna at the RF source (HAMEG RF synthesizer HM8135) have 6 dBi gain. The current consumption parameters are taken from Mica2 datasheet. Each sensor mote was equipped with 9 dBi gain directional antenna and P1110 RF energy harvesting kit. It was found that, RF-to-DC conversion was appreciable up to a maximum distance $d_{max} = 90$ cm. P1110 has a 50 mF super-capacitor which can be charged to 3.3 V. The measured power consumption of RF synthesizer while operating at $+13$ dBm output was found to be $P_{rf} = 41.27$ W. Crossbow sensor mote was programmed to transmit cyclic counts at $+5$ dBm. Its average current consumption was found to be approximately 17 mA while operating at voltage of 2.8 V, giving a power consumption of 47.6 mW. The following experimental steps were involved:

1) P1110(1) is kept at a distance d_1 from RF synthesizer which is operated to charge P1110 from 0 V to 3.3 V. Time taken for charging is say t_1 sec.

2) P1110(2) is kept further away at a distance $d = d_1 + d_2$. In t_1 sec, it gets charged to say V_1 from 0. Steps 1 and 2 are basically single-hop charging of the motes placed at distances d_1 and d.

3) The sensor mote is connected to P1110(1). It transmits at +5 dBm for $t_2 = 6$ sec before getting discharged to $V_2 = 1.7$ V (below which level the mote's operation is suspended). In that time, P1110(2) gets charged from V_1 to, say, V_3. Thus, for multi-hop energy transfer, total time consumed, $t_{ME} = t_1 + t_2$ sec, and energy consumed, $e_{ME} = P_{rf} \cdot t_1$ J.

4) For single-hop energy transfer to charge up P1110(2) to V_3, the time of operation of the RF synthesizer is: $t_{SE} = \max(t_3, t_4)$, where t_3 is the time required for charging P1110(1) at d_1 distance to $V_2 = 1.7$ V and t_4 is the time required for charging P1110(2) at d distance to V_3. Since $d > d_1$, $t_4 > t_3$, which is typically true in single-hop charging. Thus, $t_{SE} = t_4$ sec. Correspondingly, $e_{SE} = P_{rf} \cdot t_{SE}$ J.

The key experimental observations are highlighted in Table I. It can be noted that the energy saved is on the order of 100's of joules which is quite substantial. The data also indicate that, if a mote runs out of power, by energy transfer from an energy-surplus neighboring peer node it can operate in sleep mode and keep sensing, thus sustaining the network sensing operation for a longer time.

TABLE I

ENERGY AND TIME BENEFITS IN ME AS COMPARED TO SE IN ONE CYCLE OF ENERGY TRANSFER. ENERGY SPENT IN ME BY MOTE AT d_1 DISTANCE: 0.2856 J.

d_1 (cm)	d_2 (cm)	Energy saved (J)	Time saved (sec)	Energy transferred in ME to mote at d distance (mJ)	Extra time the mote can be in sleep mode (sec)
40	30	825.4	14	1.5	2678.6
30	40	412.5	4	0.9512	1698.7
40	40	412.7	4	0.97727	1745.1
50	30	701.59	11	1.5	2678.6

Note that, in one cycle of two-hop energy transfer, the node at d_1 distance is discharged to $V_2 = 1.7$ V while the node at $d = d_1 + d_2$ distance charges up to V_3 (which is $\cong V_2$). It is possible to compare the ME process with the SE where V_3 is pulled up to 3.3 V in a few number of iterations while V_2 is already saturated to 3.3 V.

With the observations on multi-hop energy transfer gain, below, we outline the complete protocol operation for maintaining uninterrupted network operation.

IV. OPTIMIZING CHARGING AND DATA GATHERING ACTIVITIES FOR NONSTOP NETWORK OPERATION

Referring to the network topologies in Figure 1, it may be recalled that, along with the availability of physical path in the network deployment terrain, the trajectory optimization is dictated by the energy sensitivity for an appreciable RF-to-DC conversion, which is much poorer (-11.5 dBm in commercially available Powercast P2110 harvester, -22 dBm in research literature [12]) compared to the receiver threshold for successful data transfer (-98 dBm in Mica2 mote). As a result, the processes of cluster-head to mobile agent data collection as well as the data aggregation from the field nodes within a cluster are always done via direct (single-hop) communication.

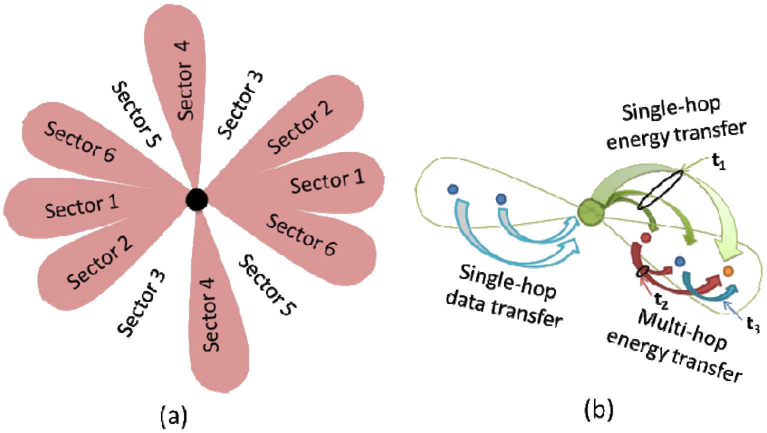


Figure 5: Beam forming approach to energy supply and data gathering: (a) Charging field nodes via beam forming and time-division multiplexing. (b) Energy supply and data collection by the cluster-head.

In each energy transfer and data collection cycle, the amount of energy available upon charging of a cluster-head should be sufficient to impart the required energy to the field nodes and complete the field data collection process. To optimally use the energy, we suggest to use steered beam forming technique (Figure 5(a)). With a half-power beam width 30° and a circular coverage range, the cluster-head needs to steer the antenna beam in 6 sectors to complete the charging and field data collection process. Due to the very different energy and data reception sensitivities and to aid energy and time efficiency, the RF energy is transferred over multi-hop (e.g., 3 hops, in Figure 5(b)), whereas the data gathering is carried out via direct communication.

In Figure 6, the timing diagram of energy transfer and data collection is shown, where it is assumed each sector is separately addressed by the cluster-head for data/energy transfer. The total interaction time among the mobile agent, cluster-head, and the field nodes in a cycle is $T_c = t_{ch} + \sum_{i=1}^{6} t^{(s_i)}$. Here, t_{ch} is the time spent when the mobile agent transfers the required energy to the cluster-head, e.g., via multi-hop wireless radiative transfer, and also collects data from the cluster-head; $t^{(s_i)}$ is the time spent in sector i ($i = 1$ to 6) to complete the energy/data transfer process by the cluster-head to/from the field nodes. Thus, the periodicity of the mobile agent's visit should be

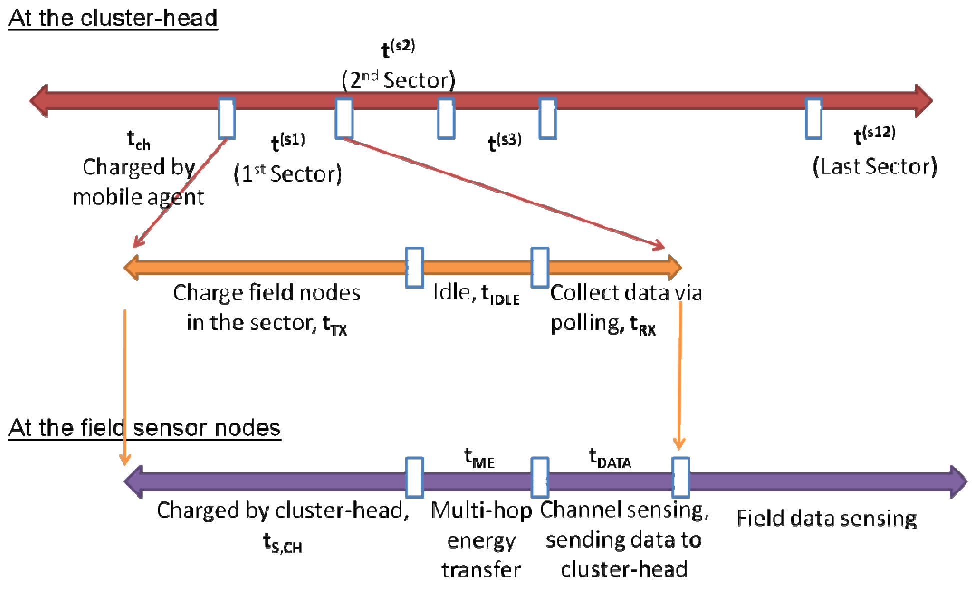


Figure 6: Timing diagram of the composite energy and data transfer protocol.

$T_p \geq T_c$. To ensure uninterrupted network operation, the upper limit of T_p is governed by the residual energy at the end of the cycle, energy decay rate at the cluster-head and field nodes in house-keeping/sleeping/sensing activities, and delay tolerance of the field sensing application. The process in a sector at the cluster-head and the field nodes have the following steps: For time t_{TX} the cluster-head radiates RF energy directly to the field nodes, the corresponding energy collection time at the field nodes is $t_{s,CH}$. During the time $t_{IDLE} = t_{ME}$, the cluster-head shuts off the radiation and lets the nearby field nodes to transfer energy to the peripheral nodes via multiple hops. Depending on sufficiency of the received energy at the peripheral nodes, the steps of duration $t_{s,CH} + t_{ME}$ may be repeated. For the remaining duration $t_{RX} = t_{DATA}$, sensors in sector i transfers data via, e.g., multi-access polling. While the cluster-head takes turn to the repeat the process in the other sectors, the field sensors go into field data sensing/ sleep mode until the next cycle of energy/data transfer.

We conducted numerical evaluation of performance using P2110 harvester and Mica2 datasheets, with all nodes transmitting energy at 5 dBm. Each field node was assumed to have 128 Bytes data per cycle of energy/data transfer. Channel errors were abstracted by taking data success rate as 80%, which gives 1.57 mJ energy consumption per field node. To replenish the energy loss at the field nodes and cluster-head, compared to the direct energy transfer, 3-hop energy transfer within a cluster showed 13.7% and 17% reduction in required time and energy, respectively.

V. CONCLUDING REMARKS

We have presented a case that, for green network operation with reduced energy supply complexity, the virtue of multi-hop wireless RF energy transfer to the field sensor nodes can be appropriately combined with the data collection mechanism by suitably deploying mobile agent. Energy and time savings achieved in multi-hop energy transfer have been quantified by numerical simulations as well as confirmed by experimental observations. By adjusting the mobility pattern of the agent and periodicity of data collection, the sensor network can be operated without interruption.

Energy sensitivity of the current state-of-the-art RF-to-DC rectifier being low, the benefits of clustered topology and multi-hop energy transfer is less. The savings are expected to increase with more advancement in low RF power rectification technology.

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