Experimental Demonstration of Multi-Hop RF Energy Transfer

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Abstract—**Batteries of field nodes in a wireless sensor network pose an upper limit on the network lifetime. Energy harvesting and harvesting aware medium access control protocols have the potential to provide uninterrupted network operation, as they aim to replenish the lost energy so that energy neutral operation of the energy harvesting nodes can be achieved. To further improve the energy harvesting process, there is a need for novel schemes so that maximum energy is harvested in a minimum possible time. Multi-hop radio frequency (RF) energy transfer is one such solution that addresses these needs. With the optimal placement of energy relay nodes, multi-hop RF energy transfer can save energy of the source as well as time for the harvesting process. In this work we experimentally demonstrate multi-hop RF energy transfer, wherein two-hop energy transfer is shown to achieve significant energy and time savings with respect to the single-hop case. It is also shown that the gain obtained can be translated to energy transfer range extension.**

Keywords— RF energy harvesting; multi-hop energy transfer; energy efficiency

I. INTRODUCTION

The constraint of limited battery energy of the field nodes in wireless sensor networks (WSN) necessitates energy efficiency. As the radio of a wireless node consumes most of the energy, the focus of research conventionally has been to reduce any unnecessary access to the shared medium, to avoid collisions, etc., by designing energy efficient medium access control (MAC) protocols, such as SMAC [1] and BMAC [2]. Recent research in WSNs focuses on energy harvesting [3] in order to increase the network lifetime. Advances in low-power microelectronics, such as the Phoenix processor [4], as well as advances in ultra-low power consuming wireless transceivers [5], have opened up the possibility for driving WSNs using network energy in tiered network architectures [6].

Much of the recent research attention has been on utilizing ambient sources of energy, such as solar [7], wind [8], ambient radio frequency (RF) [9], thermal gradient and strain from human activities [10]. But these sources are unreliable for the continuous operation of WSNs powered by ambient energy harvesting [11]. In this paper, we focus on recharging the field nodes with the help of a dedicated RF energy source, so that energy is available on demand. This technique can be combined with the other ambient energy harvesting techniques, leading to non-stop sensor network operation.

To achieve the objective of uninterrupted network operation, in addition to energy harvesting and optimal energy management policies of the energy harvesting nodes [12], approaches are required to further improve the harvesting process in terms of both energy and time spent. Our hardware experiments show that, instead of directly transferring energy wirelessly, using an intermediate energy relay node can reduce the energy spent at the RF source as well as the charging time. This additional indirect transfer of energy through an intermediate node is termed as multi-hop energy transfer.

The main contributions of our paper are: (i) experimental validation of two-hop energy transfer; (ii) demonstration of voltage and time gains, and resultant energy savings, using two-hop energy transfer; (iii) determining the optimal position of the intermediate node for maximizing the gains; and (iv) demonstration of energy transfer range extension.

The remainder of the paper is organized as follows. In Section II, we discuss state of the art for RF energy transfer and present related work from the literature. Section III presents our experimental setup, a brief overview of MICA2, and its software modifications. Pseudo code for efficient utilization of the MICA2 relay mote is provided in Section IV. Experimental results are presented in Section V. Section VI concludes the paper.

II. RELATED WORK

A. State-of-the-Art for RF Energy Transfer

Wireless transfer of RF energy can be done using an RF source, such as HAMEG RF Synthesizer HM8135. However, the main limitation of such systems is the power efficiency of the RF synthesizer, which is generally low as it is designed to operate over a large frequency range. For example the HAMEG RF Synthesizer HM8135 consumes 41.27 W power for transmitting $+13$ dBm RF power at 915 MHz.

The RF energy transmitter from Powercast operates at a frequency of 915 MHz and provides an EIRP of 3W for 5W DC input. This source, however, does not generate a continuous RF output. RF harvesters that convert RF to DC, such as the Powercast P1110 and P2110 [13], are essential to harvest the transmitted energy.

B. Literature Review

A design for an energy harvesting system was proposed in [14], and was shown to work well at power as low as -20

dBm. It is said to perform 100% better than the existing designs in the power range of −20 to 7 dBm. In [15] a rectenna was used in a modified MICA2 mote to harvest RF energy. In our work, as our aim is the realistic experimental validation of multi-hop energy transfer, we use the Powercast P1110 energy harvester with a separate antenna. We replace the MICA2 antenna with a higher gain one and program the mote for continuous transmission of energy to be harvested by the end node.

There have been very few papers in the area of multi-hop energy transfer. In [16], the authors explored the use of multi-hop energy transfer by non-radiative energy transfer. This approach requires a strong coupling for efficient transfer of energy. In [17], a feasibility study of multi-hop RF energy transfer and single hop data transfer was conducted. The authors demonstrated that under certain optimum distance conditions, multi-hop energy transfer is efficient in terms of both energy and time. Although the benefits of multi-hop energy transfer have been shown, the experiments have been performed for only a single cycle of energy transfer. The energy saved through a single cycle of energy transfer is not much and is not of much practical use. In contrast, in our current experiments, the energy transfer is conducted over multiple cycles to pull up the voltage of the energy storage device (super-capacitor) to a practically operable voltage for sensing and/or communication.

III. EXPERIMENTAL SETUP

The experimental setup consists of a MICA2 mote solely operated by the energy of the super-capacitor present on the Powercast P1110 evaluation board. The details of the individual components are presented below. The experimental setup of two-hop energy transfer is shown in Figure 1.

Figure 1. Experimental setup of two-hop energy transfer.

A. MICA2 Mote

MICA2 mote is a low power module that has processing and communication capabilities. It is normally powered by two AA batteries and operates between 2.1 and 3.3 V. It consists of an Atmega128L processor, AT45DB041B flash memory and a CC1000 transceiver radio. Dynamic power management ensures that these components are usually in sleep mode and activated only when required, as the power consumption is of the same order of magnitude in the active and idle modes, and it is much less in the sleep mode [18].

We modify the MICA2 mote such that the low gain pigtail antenna is replaced with an antenna of higher gain (= 6.1 dBi) that comes with the P1110 evaluation board from Powercast, and the mote is powered from a 50 mF super-capacitor instead of two AA batteries.

B. P1110 Evaluation Board

The P1110 Evaluation board consists of a P1110 power harvester IC that operates at 915 MHz and harvests the input power in the range of −5 dBm to +20 dBm. The output voltage from the harvestor IC can be adjusted either to 4.2 V or 3.3 V. The evaluation board also consists of a 5.5 V 50 mF super-capacitor to store the DC energy thus converted.

The experimental setup for the two-hop energy transfer involves the following components:

1. *Source:* A HAMEG RF synthesizer HM8135 is used as the RF source that transmits at a power of +13 dBm at 915 MHz frequency.
2. *Intermediate node:* An intermediate node is placed in between the source and the end node. This intermediate node acts like a relay node and is composed of the P1110 Evaluation board that harvests the input power received from the source through a 6.1 dBi antenna, converts it into DC and stores it in a 50 mF supercapacitor. It also includes a modified MICA2 mote that is powered from the energy stored inside a 50 mF super capacitor and is capable of transmitting energy in the form of data packets with the aid of a 6.1 dBi antenna. The intermediate node's maximum transmit power level is +3 dBm during ON cycle (discontinuous) as compared to the source's transmission at +13 dBm (continuous).
3. *End node:* The end node is placed farthest from the source. This is the node for which readings are recorded for the case in which there are RF transmissions from both the intermediate node and the source (*ON case (multi-hop))* and the case in which only the source transmits the energy (*OFF case (single-hop))*. The end node consists of a P1110 evaluation board that harvests the input power received from the source and from the intermediate node through a 6.1 dBi antenna, converts it to DC and stores it in a 50 mF super-capacitor.

The target of our first experiment is to find the multi-hop gain in terms of time and energy. The source and the end node are kept in line separated by 30 cm, and the intermediate node is kept in the middle at such a position that it creates the least shadowing effect and its receiver antenna connected to the P1110 evaluation board is oriented towards the source and its transmitter antenna connected to the modified MICA2 mote is oriented towards the end node. This set-up can be clearly seen in Figure 1. Thus, there are the following three transmitter-receiver pairs: 1) source-to-intermediate node, 2) source-to-end node, and 3) intermediate node-to-end node.

The objective of the second experiment is to find the optimal position for placing the intermediate node in between the source and end nodes in order to maximize the gains. The intermediate node is placed at 3 different positions, namely: closer to the source, in the middle and closer to the end node.

As the intermediate node's position is continuously varied, leading to a change in the intermediate node's receiver and transmitter antenna orientations with respect to the source and the end nodes, respectively, we kept the source - intermediate node receiver antenna and intermediate node transmitter - end node antenna pairs nearly in line. Here, the intermediate node's transmitter and receiver antennas are separated by a distance of 15 cm to reduce the effect of shadowing caused by the intermediate node. In this setting, as shown in Figure 2, we need not change the orientations every time; we can simply move the intermediate node rectilinearly.

IV. PSEUDO CODE FOR EFFICIENT ENERGY UTILIZATION

MICA2 motes utilize TinyOS, an event based operating framework that supports concurrency intensive operations with minimal hardware requirements. The original code is written in nesC. The algorithm is designed to fulfill the following requirements:

1. *Continuous RF energy transmission of mote*: MICA2 transmits energy in the form of data packets discontinuously. For energy efficiency (transferring more energy in a given time), the MICA2 mote has to be programmed to transmit packets of maximum size one after the other to imitate a continuous process. In this experiment, since we view the MICA2 mote as a potential "energy router" device rather than for data packet communication, packet errors are irrelevant.
2. *Automatic switching of radio*: The CC1000 radio of the MICA2 mote does not transmit when the voltage in the super-capacitor is below 2.1V. The fall in the voltage of the super-capacitor due to the packet transfer by the mote has to be arrested at 2.1V. Then, keeping the mote in a low power state, the voltage of the super-capacitor should be allowed to rise until it hits 3.3V by harvesting the RF energy transmitted by the source. Then, once again the packet transmission starts and the entire process is repeated. Code has to be written such that the above process takes place automatically.

The on and off durations of the radio have been determined from the charging and discharging curves of the mote. This information is used to program the mote.

Pseudo code for the continuous and automatic operation for a MICA2 mote is as follows:

```
Start the timer with firing time set to 4 ms and set count = 1
Repeat
When timer fires:
    if (count<=n), where n = (time to discharge from 3.3 to 2.1 V)/25.1 ms
        1. Start next timer with firing time = 25.1 ms (transmission time for
           max. size of packet, i.e., 241 Bytes)
        2. Start generating the packet
        3. Send the packet
        4. count++
    else if (count>n)
        1. put the mote in low-power mode for time t = time to
           charge from 2.1 V to 3.3 V
        2. set count = 1
```

V. EXPERIMENTAL RESULTS

A. Voltage Gain

The voltage level up to which the end node is charging for a fixed time has been determined in the following two cases:

1. Intermediate node transmission is ON: When both the source and intermediate node are ON, the end node charges up to a voltage, say V_{on}, in a given time interval.
2. Intermediate node transmission is OFF: When only the source node is ON, then the end node charges up to a voltage level, say V_{off}, in the same time interval.

The first case corresponds to multi-hop energy transfer, while the second case represents single hop. Three sets of readings were taken in each set-up to study the gain.

Voltage gain for the end node is defined as the ratio of voltage gained in multi-hop energy transfer, i.e., $V_{on} - V_{off}$, with V_{off}.

This experiment has been performed for three time intervals: 200 s, 300 s and 400 s. The results are tabulated and shown in Table I. A decreasing trend in voltage gain with increasing time interval can be observed from this Table. This trend is quite obvious due to the fact that, although the intermediate node transmits at the same power, the capacitor charging curve starts transitioning from the linear region to the exponential region. As a result of this, the voltage gain at longer time intervals is less than that at shorter time intervals.

TABLE I. VOLTAGE GAIN

Time interval = 200 sec				
Expt. No.	**V_{on} (V)**	**V_{off} (V)**	**Gain (%)**	**Average voltage gain**
1	1.12	0.86	30.2	28%
2	1.14	0.86	32.6	
3	1.04	0.86	20.9	
Time interval = 300 sec				
Expt. No.	**V_{on} (V)**	**V_{off} (V)**	**Gain (%)**	**Average voltage gain**
1	1.58	1.22	29.5	26%
2	1.6	1.24	29.0	
3	1.5	1.24	21.0	
Time interval = 400 sec				
Expt. No.	**V_{on} (V)**	**V_{off} (V)**	**Gain (%)**	**Average voltage gain**
1	1.9	1.56	21.8	20%
2	1.94	1.62	19.7	
3	1.86	1.56	19.2	

B. Time and Energy Gain

The time taken by the end node to charge to a fixed voltage level has been determined for the following two cases:

1. Intermediate node transmission is ON: When both the source and intermediate node are on, then the end node charges to a fixed voltage (1 V or 2 V), in T_{on} seconds.
2. Intermediate node transmission is OFF: When only the source node is on, then the end node charges to a fixed voltage level (1 V or 2 V), in T_{off} seconds.

The first case is for multi-hop energy transfer while the second case corresponds to single hop. The time saved for the end node is defined as the time gained in multi-hop, i.e., $T_{off} - T_{on}$. Time gain for the end node is defined as the ratio of time gained in multi-hop, i.e., $T_{off} - T_{on}$, with T_{off}.

As the source power consumption at +13 dBm output power is 41.27 W, the energy saved is calculated from the time saved by multiplying it with the power consumption of the source, i.e., 41.27 W.

This experiment has been performed for two fixed voltage levels: 1 V and 2 V. The results are shown in Table II.

TABLE II. TIME AND ENERGY GAIN

Fixed voltage level = 1 V						
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Time saved (s)**	**Average time gain**	**Energy saved (J)**	**Average energy saved (J)**
1	186	224	38	18%	1568	1733
2	184	232	48		1981	
3	196	236	40		1651	
Fixed voltage level = 2 V						
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Time saved (s)**	**Average time gain**	**Energy saved (J)**	**Average energy saved (J)**
1	412	526	114	21%	4705	4677
2	422	544	122		5035	
3	440	544	104		4292	

C. Distance Gain

Next we performed additional experiments to see if multi-hop energy transfer can provide any range extension. From the experiments, we observed that the time taken by the end node to charge up to 1 V when it is placed at 30 cm from the source with the intermediate node off (single hop) is the same as the time taken by the end node to charge up to 1V when it is placed at 35 cm from the source with the intermediate node on (multi-hop). So, there is a range extension of 5 cm, or about 16.7% gain in range.

D. Optimal Position of the Intermediate Node

We consider the following 3 cases:

Case A: Intermediate node closer to source
Case B: Intermediate node in the center
Case C: Intermediate node closer to the end node

Figure 2. Experimental set-up for finding the optimal position for the intermediate node.

In this experiment (set-up shown in Figure 2) we fixed the distance between the source and the end node (*d* = 30 cm) and then placed the intermediate node at distances of 10 cm, 15 cm, and 20 cm, respectively, from the source. The results show that the optimal position is when the intermediate node is closer to the source. As energy can be harvested by intermediate node at a faster rate in Case A, the intermediate node is able to transmit more energy. In Case C, the propagation loss is reduced as the distance from the end node is small, but the power received by the end node from the intermediate node is smaller than Case A due to fewer of the intermediate node's ON/OFF cycles as it is further away from the source and takes longer to charge enough to turn on. Tables III, IV, and V show the results for voltage gains in cases A, B, and C, respectively.

TABLE III. VOLTAGE GAIN FOR CASE A (INTERMEDIATE NODE CLOSE TO SOURCE NODE)

Time interval = 200 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	656	520	26.1	26%
2	744	560	32.8	
3	672	560	20.0	
Time interval = 400 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	1.26	936	34.6	32%
2	1.32	976	35.2	
3	1.22	968	26.0	

TABLE IV. VOLTAGE GAIN FOR CASE B (INTERMEDIATE NODE IN THE MIDDLE)

Time interval = 200 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	640	574	11.5	11%
2	656	584	12.3	
3	610	552	10.5	
Time interval = 400 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	1.17	1.05	11.4	12%
2	1.18	1.04	13.5	
3	1.13	1.02	10.9	

TABLE V. VOLTAGE GAIN FOR CASE C (INTERMEDIATE NODE CLOSE TO END NODE)

Time interval = 200 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	568	496	14.5	14%
2	576	496	16.1	
3	576	512	12.5	
Time interval = 400 sec				
Expt. No.	**V_{on} (mV)**	**V_{off} (mV)**	**Gain (%)**	**Average voltage gain**
1	1.06	920	15.2	15%
2	1.08	930	16.1	
3	1.08	960	12.5	

Even when we compare the results in terms of time gain for finding the optimal position, we get that Case A is the best among the three. The results for the three cases are presented in Tables VI, VII, and VIII. Thus, referring to Figure 2, it is

TABLE VI. TIME GAIN FOR CASE A (INTERMEDIATE NODE CLOSE TO SOURCE NODE)

Fixed voltage level = 0.5 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	154	186	17.2	18%
2	132	174	24.1	
3	150	170	11.8	
Fixed voltage level = 1 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	300	520	42.30	47%
2	272	560	51.42	
3	294	560	47.5	

TABLE VII. TIME GAIN FOR CASE B (INTERMEDIATE NODE IN THE MIDDLE)

Fixed voltage level = 0.5 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	154	172	10.5	11%
2	150	170	11.8	
3	158	178	11.2	
Fixed voltage level = 1 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	322	376	14.4	14%
2	316	372	15.0	
3	334	386	13.5	

TABLE VIII. TIME GAIN FOR CASE C (INTERMEDIATE NODE CLOSE TO END NODE)

Fixed voltage level = 0.5 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	176	202	12.9	14%
2	166	202	17.8	
3	166	190	12.6	
Fixed voltage level = 1 V				
Expt. No.	**T_{on} (s)**	**T_{off} (s)**	**Gain (%)**	**Average time gain**
1	372	438	15.1	16%
2	356	428	16.8	
3	356	418	14.8	

observed that Case A offers the best performance while Case B is the poorest. Although Case C has fewer ON-OFF cycles than Case B, it offers a better energy transfer performance as it has less propagation loss due to the smaller distance between the intermediate node and the end node. The advantage of having highest number of ON-OFF cycles in Case A proves to be better than the path loss advantage of Case C. However, Case B is the worst, as it neither has the advantage of more ON-OFF cycles as in Case A nor the reduced path loss advantage of Case C.

VI. CONCLUSIONS AND FUTURE WORK

In this work, multi-hop energy transfer to charge a sensor battery up to a practical operating voltage has been experimentally demonstrated. Multi-hop energy transfer has been shown to provide significant voltage, time, and energy savings. The process can alternatively be used to extend the wireless RF energy transfer range. In the tested two-hop energy transfer, the optimal position for maximizing the performance gain has been found to be when the intermediate node is closer to the source.

Currently, the intermediate node's charging and energy radiation have been programmed as timer based, which needs reconfiguration every time the node positions are altered. To make the process more generic, we are working to automate this based on the charged voltage level at the intermediate node. The current proof-of-concept test results with the off-the-shelf low-power components are limited to quite small RF energy transfer range. As future work, we intend to look into optimizing the systems-level components to extend the RF energy transfer range in indoor/outdoor settings. Finally, we will explore the use of multi-hop energy transfer in passive wake-up radio scenarios [19].

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