Design of an Active Radio Frequency Powered Multi-Hop Wireless Sensor Network

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***Abstract*—In this paper, we present a low power solution for multi-hop wireless sensor networks using active radio frequency (RF) harvesting. We show by careful design of both hardware and network protocol that it is possible to design multi-hop networks that use minimal power. We identified critical factors and incorporated them into the protocol design, which we validated by implementing a small testbed of nodes using commercially available RF energy harvesting devices. The speed at which sensor data can be retrieved from the network has been evaluated and deemed to be viable for wireless sensor networks used in low duty cycle monitoring applications.**

Keywords- RF harvesting; wireless sensor network; sink synchronized multi-hop;

I. Introduction

When deploying a wireless sensor network (WSN), there are some obvious disadvantages when batteries are used to power the nodes. Firstly, besides the need to replace the batteries once they run out, there are also situations where replacing a battery is totally infeasible such as when a wireless sensor node is embedded within a concrete building or some other place that humans cannot reach. Secondly, batteries can leak their contents into the surrounding environment, and this can lead to problems ranging from pollution of the environment to corrosion of the surrounding material and compromising the structure. This has led many to investigate innovative new solutions that avoid requiring batteries.

One such solution is to use active radio frequency (RF) energy harvesting. Active RF energy harvesting is a method whereby an RF energy transmitter (ET) transmits energy to the WSN nodes using RF waves. It is active in the sense that you need to turn on the ET before the nodes can harvest energy. Besides not needing a battery and the advantages that come with this, another advantage of active RF harvesting is having the ability to turn off the power to the nodes without touching the nodes themselves. However, using RF waves to power nodes also has some operational challenges, of which, the most critical one is the power that a node typically gets is very low if the nodes are to function at any reasonable distance from an ET transmitting at realistic power levels. Consequently, star topology networks have been used when using RF harvesting.

It is desirable that the nodes powered by RF harvesting are able to work at distances as far as possible from the ET. But, this presents problems as the amount of available RF power decreases rapidly with distance from an RF energy transmitter. Regardless of the amount of RF energy that the nodes are receiving, they always have certain unavoidable power overheads (quiescent power); as a result of this, the efficiency with which the nodes can obtain energy for useful tasks such as communicating decreases with distance. Both the rapid reduction of available RF power due to propagation loss and the reduction in efficiency with distance significantly affect the maximum distance that a node can operate at.

Another problem when using RF to power nodes is due to the way RF waves propagate which makes the amount of RF power at any particular location in space difficult to determine ahead of time and can even change over time. Both RF absorption from materials, and reflections off surfaces causing interference can make the power either more or less than what might be predicted using the RF inverse square law. The power a node receives can even change with respect to time because of objects such as people, animals and plants moving past the nodes. Nodes also generally receive very different levels of power compared to one another which can make protocol design difficult.

Due to the low power that one gets from RF harvesting, it is primarily used for applications where sensor readings are required infrequently. In this project, our target application lies in the agricultural domain where sensor readings need to be taken only a few times daily. We designed a multi-hop network that uses active RF energy harvesting and implemented a proof-of-concept prototype to validate the design. The low energy availability from RF energy harvesting constrains our design of the wireless sensor node to consume less than 10μW. In the next section, we briefly discuss related work on WSNs powered by RF energy harvesting. Following that, we present the design of the node hardware and network protocol, before discussing the experimental validation and conclusions.

II. Related Work

To the best of our knowledge, no one has investigated RF powered multi-hop WSNs nor implemented them. Previous work on using RF harvesting to power WSNs has focused on star topology networks and most, if not all studies, relied only on simulations. Simulations while interesting can be flawed due to incorrect assumptions and neglecting power overheads required in actual implementations. In addition, the absence of research into RF powered multi-hop WSNs neglects another important type of network architecture.

Obtaining energy passively using RF harvesting from TV transmitters has been researched by [1] and [2]. It has been reported in [1] that a Yagi antenna was used to obtain 60µW of usable power from a TV transmitter tower located 4km away. In [2], while it has been stated that 20µW of usable power can be obtained from a TV transmitter tower up to 6.6km away, it was only mentioned that their prototype node has been tested at distances of 500m away from the TV transmission tower, and that the node was using several hundred microwatts at this distance; the minimum power requirements for the node was not mentioned.

The RF power density of GSM cellular phone towers in residential areas in Germany have been investigated and the median power density has been found to be 200µW/m^2 [3]. Other studies, e.g. [4] and [5], have looked into the RF to DC conversion circuitry and powering the conversion circuitry using nearby cellular towers, mentioning only the voltage obtained but not usable power [5]. Furthermore, the maximum experimental distance is also somewhat limited to 50m from a cell tower.

Recently, commercial products for active RF harvesting have been made available by Powercast [6]; they produce a 3W RF transmitter and wireless sensor nodes that operate up to a few tens of meters. Their node's communication radio, microprocessor and sensor circuitry is unpowered until enough energy has been gathered, at which time the node is powered up, the sensors take readings, and the node transmits a packet; then, the microprocessor, the communication radio and sensor circuitry is unpowered once again. This approach is based on a star network where nodes closer to the RF transmitter transmit their data more often than the ones further away. A medium access control (MAC) protocol [7] has been proposed that compensates for the unfairness in power obtained by the nodes due to differing positions from the RF transmitter by allowing nodes that receive lesser power to have a higher probability of winning a transmission contention. However, their results are based on solely on simulations using the specifications of Powercast's devices, and all their graphs show transmission power levels that are more than five times the legal limit for the 900Mhz ISM band in the USA.

In [8], an active RF powered wake-up radio system has been proposed for battery powered body sensor nodes and nodes that deliver drugs on demand. This allows the nodes to respond to commands sent from a master node external from the body within a few milliseconds. In addition, the nodes do not use any energy from their batteries listening for this command because the command also contains the energy to power the wake-up radio.

III. NETWORK STRUCTURE

Of all the multi-hop networks we considered, a sink synchronized multi-hop network used the least amount of power [9]. Synchronized multi-hop networks allow nodes to turn on their radios for shorter periods of time than nodes in asynchronous networks and this saves energy. In a sink synchronized multi-hop protocol, each node must be able to hear the synchronizer but vice versa. Fig. 1 shows the network structure of our sink synchronized multi-hop network using active RF energy harvesting.

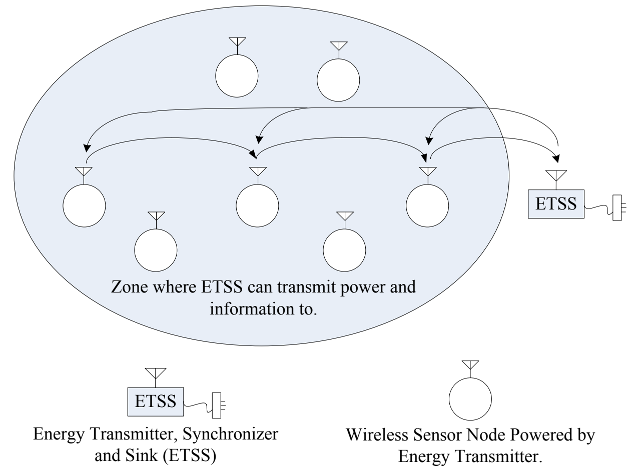

Figure 1. Sink synchronized multi-hop network using active RF harvesting.

The sink, which is also the synchronizer, is a specialized node that has no power constraints and has a much higher power communication radio so as to be able to transmit commands to all the nodes. The ET uses different frequencies to that of the communication radios so that the ET's RF waves do not interfere with the communication radio; this means the ET can power the nodes at the same time as the nodes can communicate with one another.

IV. HARDWARE

For this project, we used Powercast's 3W ET and their P2110 RF energy harvesting chips as the basis of getting energy from the mains, over the air, to the nodes. The ET transmits approximately a 60° beam of 915MHz radio waves with an Effective Isotropic Radiated Power (EIRP) of 3W. With an aerial and a 1mF intermediate capacitor, the P2110 chips receive this energy turning it into a pulsed 3.3V output. The duty cycle of this output varies depending on the power the chips are receiving from the ET and the power drawn from this 3.3V output. Our nodes connect to this pulsed 3.3V power supply output as shown in Fig. 2.

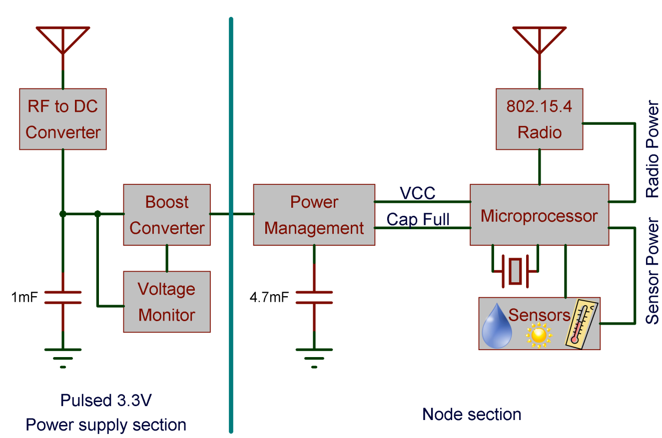

Figure 2. Block diagram of node powered by RF harvesting.

The power management block fills the node's 4.7mF reservoir capacitor when the boost converter is on and attempts to minimize the leakage from the 4.7mF back into the boost converter when the boost converter is off. When voltages are below 2.4V, the power management block disconnects the microprocessor, whilst voltages above 3.1V would prompt the power management block to signal the microprocessor that the capacitor is full by waking it up. The quiescent current of the power management block is typically less than 400nA. The output from the power management block is unregulated and will fluctuate from 2.4V to 3.3V depending on the charge left on the 4.7mF capacitor. This unregulated voltage allows the boost converter to operate at higher currents for shorter periods of time thus increasing the efficiency with which the energy in the 1mF is transformed into 3.3V.

The microprocessor block has the ability to supply regulated voltage to both the sensors, and a 2.45Ghz IEEE 802.15.4 compliant communication radio. The microprocessor uses an internal high-speed resistor capacitor (RC) oscillator for code execution, and has the ability to switch on an external crystal oscillator when precise synchronization is needed between itself and the rest of the network. The communication radio is an MRF24J40MA module from Microchip. The module, according to the datasheet, uses 63mW when receiving, 76mW when transmitting, and can transmit up to 100m. The radio module, even in receiving mode, uses over 30,000 times more power than when the node is recharging its reservoir capacitor. Energy-wise, the radio module is the most expensive component of the node.

The node is able to use less than 2µW quiescent power when recharging the 4.7mF capacitor. In this state, the microprocessor switches off all of its oscillators and can only be woken up again when the power management block signals the microprocessor that the capacitor is full. Fig. 3. shows the node prototype. The sink/synchronizer consists of a crystal-controlled microprocessor with a MRF24J40MC 802.15.4 communication module. This module, according to the datasheet, can transmit up to 1000m.

A. Usable power at distance

We measured the amount of power a node obtains after the RF to pulsed 3.3V conversion that is performed by the P2110 RF energy harvesting chips with respect to distance from the 3W Powercast energy transmitter. This was performed in a room roughly 12m × 2.4m × 3.6m. The nodes used a high gain patch antenna with a gain of 6.1dBi, which we positioned to maximize the power each node was receiving for each distance. Fig. 4 below shows the points we obtained along with a power least main squares (LMS) fit.

As shown, there is a general trend for less power when distance increases. Due to the software implementation, the network protocol we designed requires the nodes to obtain at least 7µW to function properly in a multi-hop fashion. We can see that nodes farther than 10m away from the ET can still receive enough power to allow the nodes to function properly (7µW minimum). While there is no exact cutoff point for when the nodes are unable to function properly, we found the maximum distance is generally is limited to around 12m.

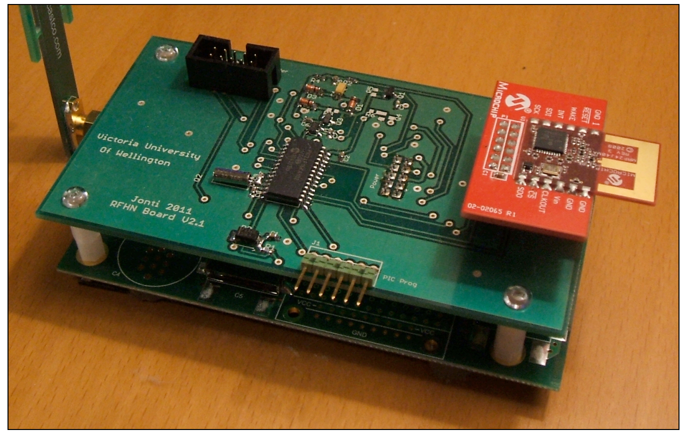

Figure 3. Node prototype

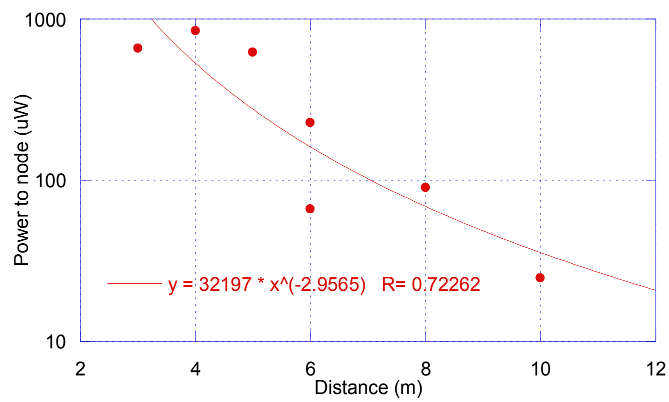

Figure 4. Power node obtains versus distance.

V. Network Protocol

Taking into consideration the constraints posed by RF energy harvesting, we designed a sink synchronized multi-hop network protocol. The nodes harvest energy and when enough energy has been gathered, the power management block wakes up the microprocessor; the node then checks for a command from the synchronizer to perform. The time between checking for commands from the synchronizer is non-synchronous between nodes and dependent on the power that the nodes are receiving. Such commands sent by the synchronizer to the nodes are to instruct the nodes to take sensor readings, discover neighboring nodes, relay data, etc. Also contained in these commands is timing information that allows the synchronizer to synchronizes all the nodes with one another, so that each node knows what all the other nodes are doing and this allows the nodes to effectively communicate with one another by enabling the nodes to listen only when other nodes are sending, thus reducing energy consumption. Due to the redundancy in the commands sent by the synchronizer, by sending each command multiple times, any node need only hear a fraction of the command transmission period to receive the command and synchronize itself with the other nodes; this allows the nodes to keep their radios in an off state more often, thus also saving energy.

The protocol does not stipulate that a node needs to check for commands from the synchronizer at particular times.

Instead the protocol stipulates what maximum time nodes are allowed between checking for commands. This happens due to the rate at which the synchronizer sends commands; if commands are sent more frequently then nodes have a shorter time between checking for commands. The flowcharts in Fig. 5 below show the command sequences sent to the nodes from the synchronizer to initialize the network and to retrieve data from the network.

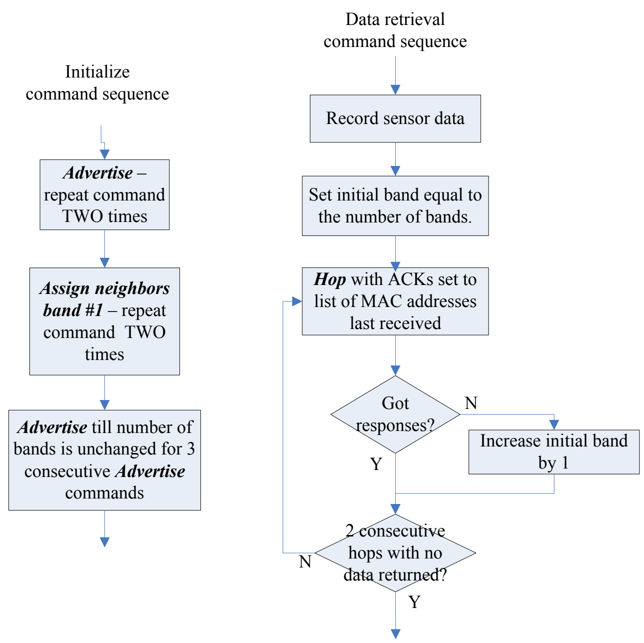

Figure 5. Command sequences for initializing and retrieving data

VI. COMMAND TIMING

A. Command recovery time

We can model the storing of energy of our nodes with a simple resistor capacitor (RC) network over the pulsed 3.3V power supply. We see that there is an inherent associated efficiency of storing energy in the reservoir capacitor as given by Eqn (1), where V_b is the voltage over the power source, while V_{cinit} and V_{cfin} are the initial voltage and the final voltage across capacitor respectively.

$$\eta = \frac{V_{cfin} + V_{cinit}}{2V_b} \qquad (1)$$

If we take into account the quiescent power that is used by the node when it is in a recharging state, we can derive an expression for the period of time a node takes to recover from a command (in the sense of recharging its reservoir capacitor) with respect to the amount of power the node receives. This is expressed in Eqn (2), where P_B is the quiescent power used by the node when recharging, P_{TOT} the power the node is receiving, E_{CMD} energy the node uses in response to the command, and t_{CMD} period of time the node takes to recover from the command.

$$t_{CMD} = \frac{E_{CMD}}{\eta_{CMD}\left(P_{TOT} - P_B\right)} \qquad (2)$$

The synchronizer commands, along with measured values of both the node's capacitor recharge recovery efficiencies of recovering from a command, and the energy used by the nodes due to each command are listed in Table 1.

TABLE I. ENERGY CONSUMPTION AND CAPACITOR RECOVERY EFFICIENCY FOR VARIOUS COMMANDS

Network Protocol Command	Energy consumption	Capacitor recovery efficiency
Assign neighbors to band #1	$2.2 \pm 0.7mJ$	$92 \pm 2\%$
Advertise	$4.2 \pm 1.0mJ$	$89 \pm 2\%$
Record sensor data	$0.78 \pm 0.25mJ$	$93 \pm 1\%$
Hop	$3mJ$ (typical)	91% (typical)
Idle	$0.87 \pm 0.19mJ$	$93 \pm 1\%$

The so-called idle command is not technically a command but behaves similar to one. The idle command refers to the node periodically checking for a command from the synchronizer and failing to receive anything because the synchronizer has not sent any command at that time.

We measured the time a node takes to recover from the idle command (t_I) for different levels of received power, and compared this with the theoretical Eqn (2) for the idle command; Fig. 6 is a graph of both our measured points along with Eqn (2) for the idle command as a comparison.

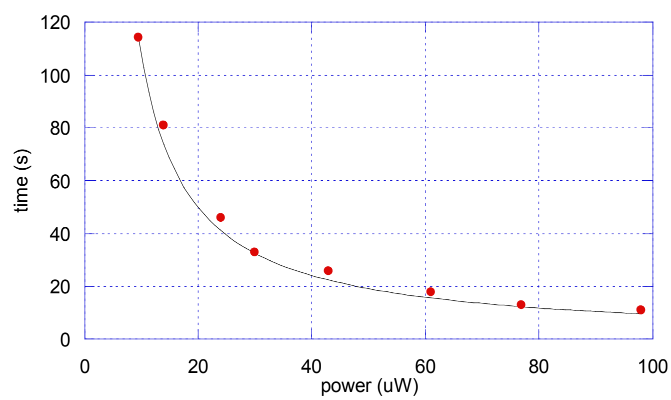

Figure 6. Measured node idle recovery command time versus received power and theoretical recovery time.

As shown, Eqn (2) does indeed predict the period of time it takes a node to recover for an idle command very well.

B. Command period

A command sent by the synchronizer consists of a transmission period (t_{TX}) where the synchronizer sends packets as fast as it can, followed by an action period (t_{Action}) where the nodes and the synchronizer perform the required action due to the command, and finally followed by a rest period (t_{Rest}) where the synchronizer does not send any packets and allows the nodes to rest. The minimum period of time the synchronizer transmits for when sending a command (t_{TX}) must be equal to the period of time a node takes to recover from an idle command (t_I); this ensures the node is able to receive the command, as well as minimizing the period of time the synchronizer needs to transmit for. Similarly, the minimum period of time that the synchronizer needs to wait before sending the next command (t_{Rest}) must be equal to the period of time the node takes to recover from the command minus the period of time it takes to recover from the idle command. The period of time (t_{Action}) required to perform the action due to a command is dependent on protocol parameters, hardware parameters, network topology, and the command itself; it is independent of the amount of power a node is receiving. For our particular implementation, all commands except for the "hop" command, t_{Action} is less than 50ms, while t_{Action} for the "hop" command is less than 4.8s.

As we are interested in the synchronizer being able to send commands to all nodes in the network, it is sufficient to calculate t_{TX} and t_{Rest} by considering only the node in the network that receives the least amount of power P_{MIN}; any other node receives more power and thus is guaranteed to have its radio on when the synchronizer sends a command to the node. This means we can calculate t_{TX} and t_{Rest} for the synchronizer by using the following two formulae obtained from Eqn (2).

$$t_{TX} = \frac{E_I}{\eta_I \left(P_{MIN} - P_B\right)} \tag{3}$$

$$t_{Rest} = \frac{E_{CMD}}{\eta_{CMD} \left(P_{MIN} - P_B\right)} - t_{TX} \tag{4}$$

For simplicity, rather than adjusting t_{Rest} and t_{Action} for every command sent, we use a worst-case scenario and use constant values for t_{Rest} and t_{Action}; in addition to simpler implementation this allows a simple conversion between total time taken and total number of commands performed.

The command period τ is simply $t_{TX} + t_{Action} + t_{Rest}$. Using a worst-case scenario of $E_{CMD} = 5mJ$, $\eta_{CMD} = 0.9$ and $t_{Action} = 4.8s$, we set the command period in the network to be Eqn (5) by using Eqns (3) and (4):

$$\tau = \frac{5555}{P_{MIN} \times 10^6 - 2} + 4.8 \tag{5}$$

C. *Initial capacitor charging*

Before sending a command to the nodes, all nodes must fully charge their reservoir capacitors. Here, we calculate the period of time we must wait before we can send commands to the network due to nodes having not fully recharged their capacitors.

As we are interested sending commands to all nodes in the network, we just consider the node in the network receiving the least amount of power P_{MIN}. Any node receiving more power than this must have filled its reservoir capacitor.

From Eqn (1), we see that by initially charging the capacitor from an empty state, the efficiency of storing energy by this process is 50%. Treating this initial charging like a recovery from a command that totally depletes the capacitor, and using Eqn (2), the time the capacitor takes to charge from an empty state is given by the following:

$$t_{Inital} = \frac{CV_{cfin}^2}{P_{MIN} - P'_B} \tag{6}$$

where P'_B is the quiescent power used when the node is initially charging, C is the capacitor rating and V_{cfin} is the final voltage across the capacitor. This is less than the quiescent power used when the node is recovering from a command sent by the synchronizer as the power management block disconnects the microprocessor, which in turn disconnects the communication radio and sensors when the reservoir voltage is less than 2.4V. For our nodes $P'_B \approx 1uW$ and can be assumed to be negligible. Therefore, we assume the period of time we must wait after turning the energy transmitter on before sending commands can be approximated with the following:

$$t_{Inital} \approx \frac{45mJ}{P_{MIN}} \tag{7}$$

VII. EXPERIMENTAL TESTBED

We constructed a testbed consisting of seven nodes in a room approximately 6m × 3.4m × 2.4m. We used one energy transmitter and one synchronizer as the sink connected to a computer for data retrieval from the network. Due to the physical space constraints, to allow more than one band to form, the communication radios of the nodes were set to the absolute minimum transmission power that the radios allowed. This had almost no effect on the amount of energy the radios used as the radios are around 99% inefficient when transmitting. This transmission power level allowed the radios to communicate with one another up to a maximum of around 2m.

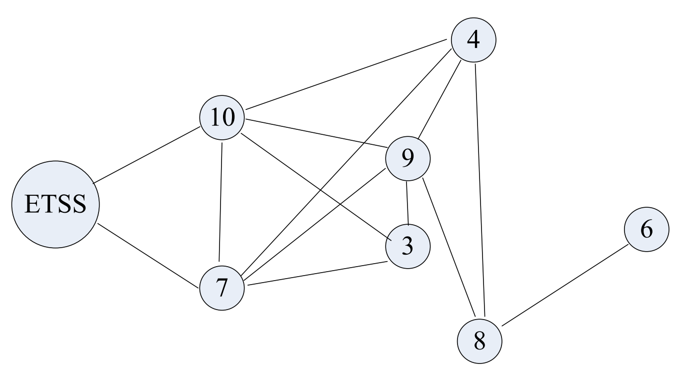

Figure 7. Most common network topology

The initialization command sequence as shown in Fig. 5 caused the nodes to group themselves in a non-pre-deterministic way. However, the most common topology for the nodes to group themselves into is shown in Fig. 7. Also shown in Fig. 7 are the nodes approximate relative positions to one another.

A value of 10μW was used as an initial estimate for P_{MIN} as Fig. 4 suggests that all nodes should be receiving more power than this because the nodes are in a room smaller than 10m. After the initial capacitor charging t_{Inital} as given in Eqn (6), initializing the network and retrieving data using this initial P_{MIN} estimate resulted in the nodes returning the approximate power they were obtaining; this allowed us to boost P_{MIN} to 80μW increasing the speed at which data could be gathered from the network. Performing 700 trials of initializing the network and retrieving data from the network resulted in requiring 15.2 ± 0.1 commands on average for each trial. As all our commands had the same period τ, the total period of time taken on average per trial was $15.2\tau \pm 0.7\%$. Using this along with Eqn (5) allowed us to calculate how long it would take for this 7-node network to be initialized and for all the data to be retrieved with respect to the amount of power being obtained by the node obtaining the least amount of power (minimum node power); Fig. 8 shows a plot of this.

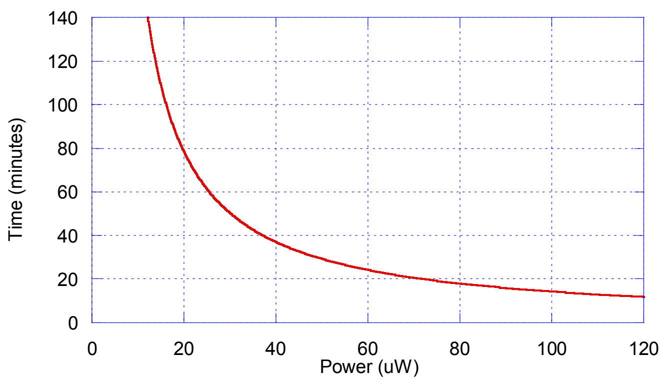

Figure 8. Time taken to initialize and retrieve data from the network versus minimum node power

VIII. CONCLUSIONS

In this paper, we have shown that indeed it is possible to design low power multi-hop networks that use RF harvesting as their source of power. The use of unregulated voltage and the energy harvesting process itself waking up the microprocessor significantly contributed to the nodes ability to work at such low power. Even with nodes receiving vastly different levels of power as one another, the sink synchronized command based multi-hop network protocol successfully was able to handle this large discrepancy by solely considering the node in the network that was obtaining the least amount of power.

Implementing a small 7-node testbed we saw that the rate at which sensor data can be obtained from the network was dependent on the minimum node power. Times ranged from a few minutes to a few hours depending on this minimum power. This makes our current implementation suitable for WSNs that require sensor data relatively infrequently and where latency is not a significant issue. To the best of our knowledge, this is the first design and implementation of a multi-hop network especially for use with RF harvesting. While we have focused on active RF harvesting, the network protocol and the hardware can be adapted to work with other types of energy harvesting such as solar, vibration, etc.

For WSNs where batteries are not an option, active RF harvesting is a potential avenue for further research. With the current state of technology, using low power ETs like the ones used in this paper, the distance at which nodes will operate from an ET is still limited. However, as technology advances and improves the efficiency of the conversion between RF energy and usable electrical energy, along with a reduction in power needed for electronic components (particularly, the communication radios) the distance at which nodes can operate from a given ET is expected to increase over the years.

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