Prototype Design and Network Protocols for
Wireless Energy Harvesting Sensors

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by
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Abstract

Radio frequency (RF) wireless energy transfer and energy harvesting from external sources promise a battery-free paradigm for resource constrained wireless sensor networks (WSNs). The objective of this thesis is to advance the engineering of these energy harvesting components interfaced with off-the-shelf motes and formulate the design of higher layer link and routing protocols for a WSN composed of such motes. The specific contributions of the thesis include: (i) optimization and implementation of RF energy harvesting circuits, (ii) medium access control protocol for scenarios with multiple energy transmitters, (iii) cross-layer protocol design that includes joint duty cycle determination and routing, and (iv) the impact of mobile energy transmitters and the relative positions of the event locations.

Our hardware design allows the energy harvesting circuit to be more receptive in low input power region over existing commercial solutions. We propose an optimization approach for choosing circuit components that enables operation within $\pm 20$ dBm of incident RF signal power. A PCB fabrication of our circuit demonstrates that it can run a commercial Mica2 sensor mote in duty cycle at $-6$ dBm incident RF power and yield 100% improvement in efficiency over existing designs. In the second contribution, through an experimental study, we demonstrate how the placement, the chosen frequency, and number of the RF energy transmitters affect the sensor charging time. These studies are then used to design a MAC protocol called RF-MAC that optimizes energy delivery to sensor nodes on request, while minimizing disruption to data communication. Our approach reveals 112% average network throughput improvement over the classical unslotted CSMA MAC protocol. Our cross-layer protocol design provides a joint hardware-software optimization by allowing the selection of the energy storage capacitor, apart from the route and duty cycle determination. We adapt AODV for this design, using new route selection metrics and route management mechanisms. Finally, we investigated the impact of mobile transmitters with two different mobility models, and provided guidelines on which of them may be adopted based on the distribution of the events and actors.

In summary, this thesis considers a holistic view of energy harvesting WSNs, from device design to its eventual deployment.
Acknowledgements

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Chapter 1

Introduction

With the growing popularity of large-scale and resource-constrained sensor-based wireless networks (example applications include structural health monitoring, human health monitoring, to name a few), the need to adopt inexpensive, energy efficient operational strategies are of paramount importance. One approach is to deploy a network comprising self-powered nodes, i.e., nodes that can harvest ambient energy from a variety of natural and man-made sources for sustained network operation [1]. This can instrument potentially leading to significant reduction in the costs associated with replacing batteries periodically. Moreover, in some deployments, owing to the sensor location, battery replacement may be both practically and economically infeasible, or may involve significant risks to human life. Thus, there is a strong motivation to enable an off-the-shelf wireless sensor network (WSN) with energy harvesting capability that would allow a sensor to replenish part or all of its operational costs, thereby taking the first steps towards realizing the vision of a perennially operating network.

Energy harvesting is the process of scavenging ambient energy from sources in the surrounding environment. It is an attractive method for overcoming the energy limitations of conventional battery powered wireless devices. One way to classify the different sources of ambient energy is into natural, artificial, and human-generated sources, and is shown in Table 1.1 along with possible wireless applications that could be powered using them.

- **Natural Sources:** Solar energy harvesting through photovoltaic conversion provides the highest power density for wireless nodes that have direct access to sunlight with an yield of 15mW/cm². This energy harvesting rate is sufficient to exchange scalar data. However, in the absence of direct sunlight, such as in indoor personal area applications, structural monitoring under the bridge, at the night time, or during the day under cloudy conditions, the harvested energy is insufficient. The use of wind as the energy source involves setting up
the nodes at a height, and a comparatively larger initial investment. However, their use has been documented for powering nodes involved in aerial wireless surveillance, and enabling sensors deployed for monitoring of forest fires.

- **Artificial Sources:** Mechanical vibration is the choice for energy harvesting in applications, such as SHM. The energy yield from mechanical vibrations, though time varying, is an order of magnitude higher than scavenging the ambient RF power emitted by TV stations, or from the conversion of light energy emitted by home appliances that can be considered to be available for fixed time durations. The most common design of piezoelectric vibration energy harvesting devices is based on cantilever resonators and targets relatively high frequency (> 30 Hz) vibration. The simple cantilever-based energy harvester is efficient only when its resonant frequency is tuned to match the environmental resonant frequency. Thus, it is still an open challenge to devise harvesters for the deployed wireless sensors on bridges, which typically have fundamental frequencies below 5Hz. Similarly, the underwater flow vibrations caused by water currents and tides are used for powering underwater acoustic sensors.

- **Human-Generated Sources:** There is considerable potential for wearable or implantable wireless sensors harvesting energy from the human body (which generates, on average, around 10.5MJ of energy per day), from sources such as blood pressure, body heat, or breathing. These sensors must periodically send health data to the external monitoring station, and thus, rely on guaranteed sources of energy. A new direction towards developing nanonetworks using molecules, instead of electromagnetic or acoustic waves, to encode and transmit the information has been proposed recently that will necessarily rely on tapping into the energy reserves (such as cellular sources) within the host body.

The above sources of energy can be further classified based on the possibility to control their availability, and determine their effectiveness as a source for harvesting for the duration of their availability. Ideally, fully controllable sources are best suited for reliable network operation, but are hard to find in the natural world. As an example solar energy is uncontrollable and non-deterministic over the entire day, due to various climate induced changes in the cloud cover. Similarly, devices based on harvesting energy caused by body movements of an active person are completely controllable, and their yield is deterministic. Thus, relying only on harvesting raises several concerns of continuous availability of energy. Other means of classifications include the magnitude of the harvested energies and the size the harvesting devices.

The concept of wireless energy harvesting and transfer is not new, rather it was demonstrated over 100 years ago by Tesla [2]. In recent times, RFID technology is a clear example of wireless
### Natural Sources

<table>
<thead>
<tr>
<th>Type</th>
<th>Max. Rate of Harvesting</th>
<th>Limitations and Drawbacks</th>
<th>Wireless Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar (Direct Sun)</td>
<td>15mW/cm²</td>
<td>Dependency on weather,</td>
<td>Video surveillance, strip-grazing</td>
</tr>
<tr>
<td>Solar (Cloudy)</td>
<td>0.15mW/cm²</td>
<td>day-time only, maintenance</td>
<td>for livestock monitoring</td>
</tr>
<tr>
<td>Wind</td>
<td>350W/m² (Fair)</td>
<td>Higher initial investment,</td>
<td>Aerial wireless monitoring, fire</td>
</tr>
<tr>
<td></td>
<td>1200W/m² (Superb)</td>
<td>intermittent flow</td>
<td>management</td>
</tr>
</tbody>
</table>

### Artificial Sources

<table>
<thead>
<tr>
<th>Type</th>
<th>Max. Rate of Harvesting</th>
<th>Limitations and Drawbacks</th>
<th>Wireless Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibrational</td>
<td>0.65mW/25cm diameter</td>
<td>Non-uniform, time varying</td>
<td>SHM, underwater coastal area sensing</td>
</tr>
<tr>
<td></td>
<td>(at 1.71kHz)</td>
<td></td>
<td>Power RFID sensor motes that can work over several meters</td>
</tr>
<tr>
<td>Ambient RF</td>
<td>60mW at 915MHz</td>
<td>High attenuation, low yield, need for large antennas</td>
<td>Building control, energy management</td>
</tr>
<tr>
<td>Incandescent Lamps,</td>
<td>6 µW/cm²</td>
<td>Number of lamps in the room, obstacles, maintenance</td>
<td>Wireless body area networks mobile phones</td>
</tr>
<tr>
<td>office Desk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 60 W Desk Lamp</td>
<td>570 µW/cm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezoelectric Energy</td>
<td>330 µW/cm²</td>
<td>Safety, efficiency,</td>
<td></td>
</tr>
<tr>
<td>(Shoe Inserts)</td>
<td></td>
<td>reliability issues</td>
<td></td>
</tr>
</tbody>
</table>

### Human-Generated Sources (for a 68 kg man during a day)

<table>
<thead>
<tr>
<th>Type</th>
<th>Max. Rate of Harvesting</th>
<th>Limitations and Drawbacks</th>
<th>Wireless Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breathing</td>
<td>930mW</td>
<td>Identification of energy sources, safety, efficiency</td>
<td>Wireless implants, pacemakers, mobile phones</td>
</tr>
<tr>
<td>Blood flow</td>
<td>830mW</td>
<td></td>
<td>Pacemakers, molecular nano-networks</td>
</tr>
<tr>
<td>Footfalls</td>
<td>67W</td>
<td></td>
<td>Two-way shortwave radio, hydraulically-driven generators</td>
</tr>
<tr>
<td>during walking)</td>
<td></td>
<td></td>
<td>Power buttons, keyboards</td>
</tr>
<tr>
<td>Finger motion</td>
<td>6.9 – 19 mW</td>
<td></td>
<td>Notebook computing</td>
</tr>
<tr>
<td>(power typing)</td>
<td></td>
<td></td>
<td>Wrist-watch, on-body sensors</td>
</tr>
<tr>
<td>Arm motion</td>
<td>60 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(intentional motion)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body heat</td>
<td>2.4 – 4.8 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carnot efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: Examples of energy sources, harvesting rates, and wireless applications.

power transmission where such a tag operates using the incident RF power emitted by the transmitter [3]. However, there are limitations in directly porting these approaches to WSN scenarios: The former cannot be scaled down for the small form factor sensors, while RFID is unable to generate enough energy to run the local processing tasks on the node, such as powering the Atmel ATmega128L microcontroller on the MICA2 mote [4]. However, given the recent advances
in energy efficiency for the circuit components of a sensor (say, diodes that require less forward voltage threshold), and the low-power operation modes supported by the device itself (say, sleep mode consuming only $\mu$W), there is a visible need for revisiting energy harvesting circuit design that can successfully operate a sensor node.

Figure 1.1 shows the components of our proposed energy harvesting circuit. The incident RF power is converted into DC power by the voltage multiplier. The matching network, composed of inductive and capacitive elements, ensures the maximum power delivery from antenna to voltage multiplier. The energy storage ensures smooth power delivery to the load, and as a reserve for durations when external energy is unavailable. Such a design needs to be carefully crafted: Increasing the number of multiplier stages gives higher voltage at the load, and yet reduces the current through the final load branch. This may result in unacceptable charging delays for the energy storage capacitor. Conversely, fewer stages of the multiplier will ensure quick charging of the capacitor, but the voltage generated across it may be insufficient to drive the sensor mote (at least 1.8 V that becomes the $+V_{cc}$ for Mica2 sensors). Along similar lines, a slight change in the matching circuit parameters alters significantly the frequency range in which the efficiency of the energy conversion is maximum, often by several MHz. Hence, RF harvesting circuits involve a complex interplay of design choices, which must be considered together. We address this problem by considering a multi-stage design of the voltage multiplier, whose operating points are decided by solving an optimization framework.

Wireless sensor networks (WSNs) are widely considered the technology of choice for different types of monitoring, data gathering, surveillance, appliance control applications, among others [5]. However, one of the most important factors preventing the extensive use of WSNs is that the lifetime of the network, i.e., the duration of the services it provides, is severely limited by energy resources: The sensor nodes are powered by short-lived batteries whose replacement or recharge...
is expensive and environmentally unfriendly, if even possible. Therefore, human assistance for battery replacements is needed, and this severely limits the monitoring applications that can be effectively performed by WSNs [6]. Moreover, as these networks get pervasive and tightly integrated into daily lives, the power drawn by thousands of nodes for their continuous operation cannot be ignored. In fact, efficient utilization of available energy resources is one of the fundamental challenges of the current century. The world energy consumption is expected to increase by 49% total, or 1.4% per year, from 495 quadrillion British thermal units (Btu) in year 2007 to 739 quadrillion Btu in year 2035 [7], and the steadily growing telecommunication sector is a major consumer of the energy resource. Thus, there is a strong motivation to integrate current WSN technology with energy harvesting capability that would allow a sensor to replenish part or all of its operational costs, and render it “perennial” from an energy point of view [8].

In many envisaged applications of WSNs, the nodes are deployed indoors, or embedded in living spaces. In most indoor deployments, the nodes may be unable to access some of the non-conventional sources of energy extensively investigated in previous research, such as solar [9], wind [10] and vibration [11]. Instead, we assume a WSN that can harvest energy from ambient radio frequency (RF) waves, which can be generated by existing wireless networks used in homes and offices, or by specialized high power wireless transmitters that intermittently emit the RF radiation. Recently prototypes for such RF harvesters have been developed in the academia [12–14], as well as commercial products have been introduced by the industry [15]. A complete energy harvesting sensor formed by interfacing the harvesting module from [15] with a Mica2 mote is shown in Figure 1.2.
While advances have been made in device design for RF powered sensors, network protocols that support these devices are still in a nascent stage. Each node receives a different amount of RF energy based on its distance from the wireless transmitter, and this too is dependent on the wireless channel conditions and the conversion efficiency of the specific circuit. For these nodes, energy savings is not obtained just by alternating between predictable “awake” and “asleep” state [16], but also through considering the (expected) energy that a node might have at a later time. Additionally, the route management must consider both the long-term suitability of a node to harvest energy by virtue of its location, and its current residual level of energy. How to tradeoff the charging characteristics of a particular device, and the requirement of keeping the entire end to end path connected with sufficient energy at each node is another key challenge.

Even though wireless energy transfer will allow deployed sensors to recharge during network operation, thereby extending their lifetimes and minimizing application downtime. Our recent research on powering Mica2 sensor motes by harvesting the energy contained in radio frequency (RF) electromagnetic waves in [14] indicated the potential for large scale deployment of this technology. However, at the protocol level, this form of in-band energy replenishment is fraught with several challenges on (i) how and when should the energy transfer occur, (ii) its priority over, and the resulting impact on, the data communication, (iii) the challenges in aggregating the charging action of multiple transmitters, and (iv) impact of the choice of frequency. Thus, the act of energy transfer becomes a complex medium access problem, which must embrace a cross-disciplinary approach incorporating wave propagation effects and device characteristics, apart from the classical link layer problem of achieving fairness in accessing the channel. This thesis is concerned with a design of a CSMA/CA based MAC protocol for such RF energy harvesting sensors, inspired by experimental evaluations on our testbed. We first identify the main issues concerning our protocol below.
1. **Choosing active energy transmitters**: An example network architecture, with stationary, omni-directional energy transmitters (ETs) $x$, $y$, and $z$, is shown in Figure 1.4. The sensor $S_1$ can be charged either through a unilateral action of any of the ETs, or through a coordinated transmission of multiple ETs. Interestingly, the joint action can only be beneficial if the arriving waves at sensor $S_1$ are aligned in phase. Hence, ETs $x$ and $z$ may together transmit, both being at a multiple of the signal wavelength $\lambda$ away (which translates in a phase difference that results in ‘constructive’ interference). While the sensor can also be charged by ET $y$, combining the action of $y$ with either of the others diminishes the performance (owing to $y$ causing ‘destructive’ interference with respect to $x$ and $z$).

2. **Energy charging time**: When the node $S_1$ requests energy from the neighboring ETs, which specific combination of ETs are selected may depend on whether only node $S_1$ needs to be recharged, or there exist other sensors (say, $S_2$) that can also potentially benefit. As the location of the ETs is critical for optimal energy transfer, this condition of benefiting a larger set of sensors requires careful coordination and ET selection.

3. **Energy vs. data channel access**: As ETs transmit at comparatively higher energy levels in the same band (3 W using Powercaster transmitter [15] in our testbed, compared to $-20$ dBm for the Mica2), a much larger area is rendered unusable for data communication. Thus, even if $S_2$ is situated at a considerable distance away from ET $x$, it will still fall within its interference band (shown by the area with dotted lines) and unable to receive data. Thus, when should a sensor actually request energy and its impact on the communication network throughput is a serious issue that needs to be investigated.

Our MAC protocol that works with RF energy harvesting, called as RF-MAC, ensures optimal
energy delivery to the requesting node. In RF-MAC, a node broadcasts its request for energy (RFE) packet containing its ID, and then waits to hear from the ETs in the neighborhood. These responses from ETs are called cleared for energy (CFE) pulses, which are simple, time-separated energy beacons. These pulses may be transmitted by more than one ET concurrently as overlapping CFEs need not be distinguished. Rather, the concurrent emission of the CFEs increases the received energy level at the sensor, and this indicates a higher number of potential transmitters from the energy requesting sensor. The responding ETs are then classified into two sets, based on rough estimates of their separation distance from the energy requesting node to minimize the impact of destructive interference as much as possible. Each set of ETs is assigned a slightly different peak transmission frequency (separated by only few KHz, hence still called in-band as the channel separation is typically 5 MHz for 802.11) so that each set of ETs contributes constructively to the level of RF energy received at the node.

While we draw the basic CSMA/CA mechanism in the 802.11 standard for the data access mechanism [17], there are several points of departure from the classical implementation. We separately select and dynamically vary the slot time, the inter-frame spacing, and the contention window size for both energy transfer and data communication. In effect, we prioritize two different aspects: the channel access for energy recharging as well as the transmission opportunity for data transfer based on a variety of energy considerations.

Powering battery constrained sensors with energy harvesting (EH) has resulted in a new paradigm of long-lived wireless sensor networks (WSNs). Such sensors may rely on external, and possibly ambient sources of energy, such as the sun, wind, naturally occurring vibrations, among others, and convert these forms of energy into useful electrical energy that is stored in a capacitor for later use. However, these sources exhibit spatial and temporal variations in the energy that is actually incident on the harvesting circuits, which makes complete dependence on these sources a major concern. Recently, we demonstrated a new technique of powering sensors through electromagnetic radiation in the radio frequency (RF) range [14], which can result in a directed energy transfer. The last aim of this thesis is to investigate scenarios where the source of energy is mobile, and has power control. Thus, how to move along Event Points (EP) in a WSN while ensuring maximum energy transferred to the sensors in need is the topic of focus in this work.

In this thesis we use the term actor to indicate an energy-rich source, which is mobile and can move around in the network. It radiates energy through RF transmissions, which is captured and converted by the on-field sensors connected to energy harvesting circuits. In the architecture considered in this thesis, the actors move under different mobility models. They also radiate power at different levels depending upon the distance from the event. We assume that the sensors around the event location are maximally impacted by the event, i.e., they perform tasks of of sensing, reporting the readings, compressing measurements based on correlation and aggregating
The data from neighbor. These activities not only involve higher transmission costs, but also higher expenditure from on-board computations. Thus, the primary aim of the actor is to ensure that the nodes around the event are kept alive, and any variation in the radiated power is always bounded by the minimum RF power level incident at these event locations. Moreover, as the actors move, they themselves consume energy, and path planning needs to be carefully considered in the design.

In this study, we look at an in-depth evaluation of multiple additional factors including the effect of sensor duty cycles, amount of actors, number of event locations, the minimum required power to charge for a given sensor, the density of sensor deployment, and the frequency in which the radiation occurs.

### 1.1 Contribution of the Thesis

We summarize the main contributions of our work as follows:

- We propose a circuit design tuned to the unlicensed ISM band at 915 MHz composed of commonly available off-the-shelf components, such as zero bias Schottky diodes HSMS-2822 and HSMS-2852, with printed circuit boards (PCBs) that can be fabricated at marginal costs. This will ultimately result in mass deployment of harvesting boards along with the sensor nodes.

- We propose a dual-stage design, one that is most efficient at extremely low input RF power (say, low power design or LPD), and the other at comparatively higher range (say, high power design or HPD). We develop an optimization framework to decide the switchover point between these two sister-circuits so that the fabricated circuit as a whole delivers the highest achievable efficiency in the operational incident power range of $-20 \text{ dBm}$ to $20 \text{ dBm}$.

- We demonstrate the interfacing of our circuit with a commonly available Mica2 sensor mote, and then characterize through experiments, the impact on the duty cycle of such an integrated device that is powered by harvesting alone.

- We undertake a rigorous performance evaluation and compare the design solutions from simulation, under ideal and non-ideal conditions, with the real PCB fabrication, and also with the state of the art commercially available products in terms of efficiency and generated voltage. The non-ideal simulation provides a bound on achievable efficiency with respect to a particular design.

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1 The 915 MHz ISM band is chosen as it allows direct comparison with the commercial solution from Powercast, also operating in the same band. Our design can be tuned to other frequency ranges as well.
We propose the use of multiple input antennas to increase the amount of energy harvested. The simulation result shows that it is feasible although there exists a bound on numbers of antennas implemented.

Moreover, we propose two cross-layer protocols that assign a charging-discharging cycle to each node at the link layer, and then identify the best possible route from the source node to the sink. We call these as (i) device-agnostic (DA), and (ii) device-specific (DS) protocols, each of which is suited to a different application scenario. The network architecture is described in Figure 1.3 with the sensors deployed randomly in the study area. The RF sources are represented by $T_1$, $T_2$, and $T_3$ that are connected to a power source. Each of these power transmitters is effective within a coverage region, shown in the figure by shaded circular regions. Both the DA and DS protocols aim to find the path from node $s_1$ to base station under the following different conditions:

- **Device-agnostic Protocol:** This method allows each node to independently identify its energy harvesting capability, in terms of the time to charge its storage capacitor. The routing metric uses this time, which we have experimentally determined to be a function of the node location, to decide the suitability of the node’s participation in a route. The advantage of this method is that it not only eliminates the need for fine grained study of the specific received RF power at the node antenna, but also it is independent of the type and characteristics of the harvesting module used with the mote (hence, device agnostic). All the nodes of the path follow the optimal charging-transmission cycle (even if their own charging times may disagree). In DA, the optimal route and duty cycle are tailored for the source to destination nodes. Consequently, the DA protocol yields the optimal result if all routes in the WSN are completely non-overlapping. However, it is possible that nodes in the route also belong to other routes. In this case, the optimality of DA is not guaranteed since nodes that participate in more than one route may encounter premature energy depletion. A preliminary study of this method is presented in [19].

- **Device-specific Protocol:** This method allows any routes to be formed, without restrictions. It creates a single network-wide schedule that allows each node to transmit and re-charge with exact synchronization. However, it requires a meticulous characterization of the harvesting circuit, knowledge of the received power value, operational power usages for the sensor, the rate of energy storage capacitor discharge during charging, transmission, and reception, among other parameters, which can either be obtained through measurements or through manufacturer specifications (hence, device specific). We describe a carefully performed study of the Mica2 mote interfaced with the Powerharvester receiver to formulate a joint PDF of energy availability for a given node. Finally, such characterization curves for all the sensors are then combined at the base station to identify the best schedule for the
network. A key benefit of the DS scheme over the DA scheme comes from the joint optimization of the hardware of the energy harvesting sensor (i.e., the choice of the capacitor) and the other network parameters, such as the duty cycle. Hence, application requirements, such as bounds on path latency, can be mapped much better to the WSN deployment, as this method provides an additional control on the design, instead of the pure network-only decisions.

The core contributions of our proposed MAC protocol for sensors powered by wireless energy transfer, called RF-MAC, can be summarized as follows:

- We experimentally identify the operating constraints of the RF energy transferring MAC protocol using actual wireless energy harvesting circuits interfaced with Mica2 motes. We demonstrate how two slightly separated energy transfer frequencies can be assigned to ETs to improve the constructive interference of their collective action.

- We design a MAC protocol to balance the needs of efficient wireless energy delivery and data exchange. We bridge these dissimilar concepts by establishing the importance of a node in the data communication, which in turn quantifies how much should the node charge.

- We analytically establish optimality conditions for the energy transfer, and create a strongly coupled protocol that operates on link layer metrics with the awareness of both the underlying hardware and fundamental limits of RF energy harvesting.

Finally, we propose two event-specific mobility models, where the events occur at the centers of a Voronoi tessellation, and the actors move along either (i) the edges of the Voronoi cells, or (ii) directly from one event center to another. We undertake a comprehensive simulation based study using traces obtained from our experimental energy harvesting circuits powering Mica2 motes. In summary, the main contributions of this study are:

- We explore the tradeoff between (i) whether to transmit at high power from a distance, or (ii) move closer to the event area to decrease the required power to transmit, with the resulting impact on the energy loss due to motion.

- We earlier designed and interfaced two prototypes that harvest energy from licensed in the 642 MHz, and the easily accessible ISM bands [14]. Here, we study if the energy transfer efficiency in the licensed frequencies justify the additional licensed user avoidance overhead.

- We identify which of the environmental factors (e.g., node density, event density, actor density, mobility pattern, transmission power variation) are dominant in ensuring long network lifetime.
1.2 Outline of the Thesis

The dissertation explores and verifies the feasibility of implementing the RF energy harvesting sensor network. We investigate the problem in both hardware design level to the design of protocols. In hardware design, we address the existing problems that deem RF energy harvesting sensor infeasible and show that, with our proposed design, this indeed can be accomplished. Moreover, our protocol design consolidates the feasibility of practical implementation. The dissertation is organized as follows:

In Chapter 2, we give a comprehensive survey of the related work produced by the research community on RF energy harvesting. We cover selected publications that have a high impact on research community, in both RF energy harvesting circuit and protocol design.

In Chapter 3, we present a dual-stage energy harvesting circuit composed of a 7-stage and 10-stage design. First, we provide guidelines on component choice and precise selection of the crossover operational point for these two stages between the high (20 dBm) and low power (-20 dBm) extremities. Second, we fabricate our design on a PCB to demonstrate how such a circuit can run a commercial Mica2 sensor mote, with accompanying simulations on both ideal and non-ideal conditions for identifying the upper bound on achievable efficiency.

In Chapter 4, we present two cross-layer approaches, called as device-agnostic (DA) and device-specific (DS) protocols, for such networks composed of energy harvesting boards connected to off-the-shelf available sensors. These protocols determine the routing paths and the harvesting-transmission duty cycle at each hop under different conditions: The DA scheme relies purely on the local measurements on the harvesting capability of a node after the sensors are deployed, and is useful for single-flow networks. The DS scheme provides a joint hardware-software optimization by allowing the selection of the energy storing capacitor, apart from the route and duty cycle determination. Both the schemes rely on a rich set of device-level experimental studies that help provide exact performance characteristics in practical scenarios.

In Chapter 5, the MAC protocol design for sensors powered by wireless energy transfer, called RF-MAC, is presented. In the course of the protocol design, we describe mechanisms for (i) setting the maximum energy charging threshold, (ii) selecting specific transmitters based on the collective impact on charging time, (iii) requesting and granting energy transfer requests, and (iv) evaluating the priority of data communication as opposed to energy transfer.

In Chapter 6, We investigated the impact of mobile transmitters and proposed two event-specific mobility models. We undertook a comprehensive simulation based study using traces obtained from our experimental energy harvesting circuits powering Mica2 motes. Our results provide guidelines on which mobility model may be adopted based on the distribution of the events and actors.
In Chapter 7, the summary of the accomplished research in this thesis is given.
Results from the research presented in this thesis have been published in [14] and accepted for publication in [20–22].
Chapter 2

Related Work

Energy Harvesting has been in the focus of the research community in recent years. There are numerous sources of power that energy harvesting can benefit from, and solar energy harvesting is one of the key examples since it has the highest energy density among other candidates. However, it has a drawback of being able to operate only when sunlight is present. In [1], a solar energy harvesting module is used to power a sensor mote. Vibrational energy harvesting is presented in [23] while harvesting energy from thermoelectric device attached to human is discussed in [24]. Small amount of work has been done on RF energy harvesting due to its low energy density. Wireless Battery Charging System using Radio Frequency Energy Harvesting is discussed in [25]. RF energy harvesting with ambient source is presented in [26] where energy harvester can obtain 109 $\mu$W of power from daily routine in Tokyo. In [27], the energy of 60 $\mu$W is harvested from TV towers, 4.1 km away, and is able to operate small electronic device. Ambient RF energy harvesting with two systems has been studied in [28]. The first is broadband system without matching while the second is narrow band with matching. The preliminary results indicate that the harvested energy is not sufficient to directly power devices but could be stored for later use. In [29], the authors investigate the feasibility and potential benefits of using passive RFID as a wake-up radio. The results show that using a passive RFID wake-up radio offers significant energy efficiency benefits at the expense of delay and the additional low-cost RFID hardware. Recently prototypes for such RF harvesters have been developed in the academia [30][31], as well as commercial products have been introduced by the industry [15]. However, we have evaluated the Powercast lifetime power evaluation and development kit and it does not perform well under an RF environment, with incident power 0 dBm and lower. Consequently, there is a need to develop an energy harvesting circuit that performs well under these low power conditions.

Our proposed RF energy harvesting circuit is based on the voltage multiplier circuit, which was
invented by Heinrich Greinacher in 1919. Later in 1951, John Cockcroft and Ernest Walton used this concept in their research to accelerate particles to study the atomic nucleus and were awarded a Nobel Prize in Physics [32]. A basic schematic of a Villard voltage doubler, sometimes also called Cockcroft-Walton voltage multiplier, and Dickson voltage multiplier are shown in Figure 2.1(a) and Figure 2.1(b), respectively. According to [33], Both Villard and Dickson topology reveal no significant difference in performance.

Maximizing the steady state data flow from the source node to the destination, under constraints of power, bandwidth, and the rate of harvesting is explored in [34]. The proposed self-adapting maximum flow (SAMF) routing strategy finds feasible paths while automatically adapting to time-varying operating conditions. The routing algorithm always route packets across the path with maximum residual capacity to the sink. The complexity of the routing algorithm is hidden behind the real-time computation of residual path capacities. In principle, in fact, routing metrics should be recomputed at each node (and possibly diffused) whenever a data packet is processed or an environmental change is detected. This poses a huge computational power to the sensors which are in essence are very short in harvested power. A geographic routing protocol D-APPOLO for asynchronous energy-harvesting WSNs is proposed in [35]. It periodically and locally calculates the duty-cycle of each node, based on an estimated energy budget for each period which includes the currently available energy, the predicted energy consumption, and the energy expected from the harvesting device assuming solar cells rated at 200–300 mWh. For the algorithm to work, the sender must know the duty cycle of the receiver in advance, and can then wait for the receiver to be ready to receive the packet. The energy aware distance vector routing (EADV) protocol is devised for sensor motes that are powered by small solar cells and use capacitors for storage [36]. One of the factors influencing the route decision is a cost metric, that is determined by the overhead of gathering the energy. For the capacitor, the quality factor (Q-value) determines the energy loss rate within the device, and therefore routes must be chosen that minimize Q to prevent waste of
energy. However, this scheme does not address the performance metrics of the network, e.g. the throughput, delay, among others. [37] incorporates the node’s residual voltage $V_{\text{res}}^i$ into the route forming decision in AODV (in addition to the classical sequence number and hop count) so that the final selected route has the longest lifetime. Each node $i$ maintains its own fractional residual voltage value, which serves as the decision metric, as $\frac{V_{\text{full}}}{V_{\text{res}}}$. During route formation a summation of the above metric for the nodes in the path is calculated, and the path with lowest cost, i.e., $\sum_i \frac{V_{\text{full}}}{V_{\text{res}}}$, is chosen. Thus, nodes that have lower cost metric, i.e., lower residue voltage ratio, will be more favorable during route formation in VA scheme.

At the link layer, there have been several efforts towards identifying optimal charging-transmission cycles. [38] analyzed the requirements for “energy neutral,” i.e., matching energy consumption to production. Also an attempt has been made to model the energy source and to adjust the energy the node’s duty cycle based on the expected available energy. At the beginning of each slot, the node evaluates its received power from the energy source and also the power drawn by the load. If the actual received power is less than the predicted received power, the duty cycle will be reduced gradually in the next cycles to compensate for the shortage of energy. In the opposite case, we want to increase the duty cycles used in the future to utilize the excess energy received in recent time slot. Although this method only discusses finding the optimal duty cycle and it does not provide the details how to use the duty cycle in a networked fashion. In addition to dynamic duty cycling algorithms, [16], analyzed the performance of the conventional MAC schemes like CSMA and ID Polling on WSNs with ambient energy harvesting capabilities. This work shows the ineffectiveness of conventional MAC schemes for ambient energy harvesting capabilities and the need for the design of new schemes.

MAC protocols that aim for energy conservation have been extensively explored in the recent past, with a comprehensive classification and survey on this topic presented in [39]. Specific to the scenario of RF energy transfer, the protocol proposed in [40], and its subsequent analytical model in [41], adopts a duty-cycle based on the proportion of harvested energy. However, this protocol requires a strict centralized base station control and relies on out-of-band RF power transfer, which does not result in the added complexity we observe in our in-band case. In [42], the authors evaluate conventional MAC protocols, such as the classical TDMA and variants of ALOHA under a packet deliverability metric, assuming again out-of-band RF transfer.

In [43], the authors present multiple concepts for multi-hop wireless energy transfer (such as store and forward vs. directly single hop transfer) and derive the efficiency of each method using inductive coupling first demonstrated in [44]. However, this non-radiative transfer is shown to work up to $2\text{m}$ and requires perfectly aligned coils of $25\text{cm}$ radius among the source and receiver nodes, not feasible in a randomly deployed network. RFID technology comes closest to the energy transferring paradigm, where a tag operates using the incident RF power emitted by the
transmitter \[3\]. However, there are limitations in directly porting these approaches to networking scenarios since RFID is unable to generate enough energy to run the local processing tasks on the node, such as powering the Atmel ATmega128L micro-controller on the Mica2 mote \[4\].

Energy harvesting from RF waves constitutes a new paradigm \[45\], that goes beyond the commonly assumed forms of energy obtained from wind \[46\] and the incident sunlight \[1\]. The viability of this technology has been demonstrated through different commercial and research prototypes \[47–50\], apart from our own efforts in \[14\]. The overall aim remains to obtain enough energy to charge a capacitor up to \(1\) – \(3\) V that can run a low-power sensor mote. The concept of actors that react to events and address them has been explored in \[51\]. Our actors are mobile and enabled with a perennial source of power. These actors may move under a variety of mobility patterns. For the purpose of this paper, we assume that the actors move along certain specific paths, based on where the events actually occur. This allows focused charging of the sensors at those event locations. We make the use of Voronoi tessellations in this work, where the area is split into regions, called as Voronoi cells \[52\].
Chapter 3

Optimization and Implementation of RF Energy Harvesting Circuits

In this chapter, we present the design optimization of RF energy harvesting circuits. In the course of our circuit design, we study the impact of an individual parameter, i.e., choice of diodes, number of stages, etc., on the output of the energy harvesting circuit. This study, presented below, is then used in the optimization framework of the energy harvesting circuit.

3.1 RF Energy Harvesting Circuit Components

The main challenge faced in harvesting RF energy is the free-space path loss of the transmitted signal with distance. The Friis transmission equation relates the received \( P_r \) and transmitted \( P_t \) powers with the distance \( R \) as:

\[
P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi R} \right)^2
\]

where \( G_t \) and \( G_r \) are antenna gains, and \( \lambda \) is the wavelength of the transmitted signal. The received signal strength, diminishes with the square of the distance, requires special sensitivity considerations in the circuit design. Moreover, FCC regulations limit the maximum transmission power in specific frequency bands. For example, in the 900 MHz band, this maximum threshold is 4 W [53]. Even at this highest setting, the received power at a moderate distance of 20 m is attenuated down to only 10 \( \mu \)W. We describe a new circuit design in this section that is capable of scavenging energy with high efficiency, beginning with the selection of the circuit components. We choose the
Dickson topology (Figure 2.1(b)) as the parallel configuration of capacitors in each stage reduces the circuit impedance, and hence makes the matching task simpler. In the following, we describe the parameters that influence selection of the circuit components, and the design strategies for efficiency in performance.

### 3.1.1 Choice of Diodes

One of the crucial requirements for the energy harvesting circuit is to be able to operate with weak input RF power. For a typical $50 \, \Omega$ antenna, the $-20 \, \text{dBm}$ received RF signal power means an amplitude of $32 \, \text{mV}$. As the peak voltage of the AC signal obtained at the antenna is generally much smaller than the diode threshold [33], diodes with lowest possible turn on voltage are preferable. Moreover, since the energy harvesting circuit is operating in high frequencies, diodes with a very fast switching time need to be used. Schottky diodes use a metal-semiconductor junction instead of a semiconductor-semiconductor junction. This allows the junction to operate much faster, and gives a forward voltage drop of as low as $0.15 \, \text{V}$. In this thesis, we employ 2 different diodes from Avago Technologies, HSMS-2822 and HSMS-2852. The former has the turn on voltage of $340 \, \text{mV}$ while the latter is at $150 \, \text{mV}$, measured at $1 \, \text{mV}$ and $0.1 \, \text{mV}$, respectively. Consequently, HSMS-2852 is suitable for LPD used in the weak RF environment, while HSMS-2822 is preferred for HPD in the strong RF environment. Saturation current is another critical parameter that impacts the efficiency of diodes. It is desirable to have diodes with high saturation current, low junction capacitance and low equivalent series resistance (ESR). Moreover, diodes with higher saturation current also yield higher forward current, which is beneficial for load driving. However, higher saturation current is usually found in larger diodes, which have higher junction and substrate capacitance. The latter two parameters can introduce increased power loss, where the benefit of higher saturation current is lost.

### 3.1.2 Number of stages

The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. Each stage here is a modified voltage multiplier, arranged in series. The output voltage is directly proportional to the number of stages used in the energy harvesting circuit. However, practical constraints force a limit on the number of permissible stages, and in turn, the output voltage. Here, the voltage gain decreases as number of stages increases due to parasitic effect of the constituent capacitors of each stage, and finally it becomes negligible. Figure 3.1 and 3.2 shows the impact of number of stages on efficiency and output voltage of energy harvesting circuit, respectively. We have used Agilent ADS with parameters sweep of $-20 \, \text{dBm}$ to $20 \, \text{dBm}$
Figure 3.1: Effect of number of stages on the efficiency of Energy Harvesting Circuit for the input RF power and varies numbers of circuit stages from 1 to 9 stages. The circuit stage in simulation is a modified voltage multiplier of HSMS-2852, arranged in series. We observe that the circuit yields higher efficiency as the number of stages increases. However, as more stages are introduced, the peak of the efficiency curve also shifts towards the higher power region. The voltage plot shows that higher voltage can be achieved by increasing number of circuit stages, but a corresponding increase in power loss is also introduced into the low power region.

3.1.3 Effect of Load Impedance

It is important that the load impedance be carefully selected for a specific energy harvesting circuit, whose impact on the circuit performance can be seen in Figure 3.3. We simulate the effect of load impedance on the efficiency of the energy harvesting circuit using Agilent ADS with parameters sweep of $-20 \text{dBm}$ to $20 \text{dBm}$ and $1 \text{K\Omega}$ to $181 \text{K\Omega}$ for input RF power and load value, respectively. We observe that the circuit yields the optimal efficiency at a particular load value, that is, the circuit’s efficiency decreases dramatically if the load value is too low or too high. The energy harvesting in simulation is 5-stage circuit, each stage is a modified voltage multiplier of HSMS-2852, arranged in series. For the particular case of WSNs, the sensor mote draws a different amount of current when it is in the active (all radios operational), low-power (radios shut down for short interval but internal microcontroller active), and deep-sleep (requires external interrupt signal to become active again) states. To correctly identify the impedance in the deep sleep state, where we presume the node harvests energy, we measure the voltage and current of Mica2 sensor mote in deep sleep.
Figure 3.2: Effect of number of stages on the output voltage of Energy Harvesting Circuit

state to consume 30 $\mu$A at 3.0 V, which translates to a 100 K$\Omega$ resistive load. A 100 K$\Omega$ resistive load is further used in our optimization.

### 3.1.4 Effect of RF Input Power

Since the energy harvesting circuit consists of diodes, which are non-linear devices, the circuit itself exhibits non-linearity. This implies that the impedance of the energy harvesting circuit varies with the amount of power received from the antenna. Since the maximum power transfer occurs when the circuit is matched with the antenna, the impedance matching is usually performed at the a particular input power. Figure 3.4 depicts the effect of RF input power, ranging from $-20$ dBm to 20 dBm, on the impedance of the energy harvesting circuit. The non-linearity in operation is shown by a sharp bend at 5 dBm. This further motivates our approach of a clear separation of two optimized sister-circuits of the LDP and HDP, where each has its own (reasonably) constant impedance.

### 3.2 Optimization Framework

The aim of this optimization framework is to maximize the efficiency of the energy harvesting module throughout the range of $-20$ dBm to 20 dBm, subject to several device and performance
Figure 3.3: Effect of load impedance on the efficiency of energy harvesting circuit

constraints. The conversion efficiency is defined in [54] as,

\[ \eta_c = \frac{DC \text{ Output Power}}{Incident \text{ RF Power} - \text{Reflected RF Power}}. \]  

(3.2)

whereas, the overall efficiency is given by:

\[ \eta_o = \frac{DC \text{ Output Power}}{Incident \text{ RF Power}}. \]  

(3.3)

Conversion efficiency is defined as a ratio of DC output power of energy harvesting circuit to net RF input power incident at the input end of the circuit. Consider a plot that measures the efficiency of the circuit against the input power, also called as the efficiency curve. The intersection of the two efficiency curves of the LPD (using the HSMS-2852 diode) and HPD (using the HSMS-2822 diode) circuits, called as the crossover point, splits the overall target range of −20 dBm to 20 dBm into two.

Conversion efficiency does not take impedance mismatch into account, and hence reflected power is subtracted from received power from the antenna. Consequently, conversion efficiency is a good parameter to measure the efficiency of only the adaptations we propose in the voltage multiplier circuit. On the contrary, overall efficiency is defined as a ratio of DC output power of energy harvesting circuit to incidental RF power at the antenna. It also includes the effect of reflected RF in the calculation. Therefore, overall efficiency provides a complete representation of the energy harvesting circuit performance, since matching network is also considered in the efficiency calculation. We use the overall efficiency \( \eta_o \) as the main performance metric in this

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Figure 3.4: Effect of RF Input Power on the impedance of the energy harvesting circuit

thesis according to this reason, which is the sum of two curves on either side of the crossover point.

Figure 3.5 shows the two efficiency curves of energy harvesting sister-circuits. The efficiency curves $f_1(x)$ and $f_2(x)$ belong to LPD and HPD circuits, respectively. The crossover point, $\gamma$, is the point where one of these two circuits become the lead contributor to the total harvested energy. Thus, the LPD is operational if the RF input power is lower than $\gamma$, otherwise the HPD circuit is operational.

As shown in Figure 3.5, there are $\frac{(\beta-\alpha)}{\text{stepsizes}}$ potential crossover points between $\alpha$ and $\beta$. At each particular crossover point $\gamma$, the total area under efficiency curve is the cumulative sum of the area under the two distinct efficiency curves corresponding to the LPD and HPD designs, one on either side of the crossover point $\gamma$. The total area under efficiency curve is hence,

$$\text{Area}_{\text{total}} = \int_{\alpha}^{\gamma} f_1(x) \, dx + \int_{\gamma}^{\beta} f_2(x) \, dx.$$  \hspace{1cm} (3.4)

The crossover point, $\gamma$, can be determined as follows:

$$\gamma = \arg \max_{\gamma} \left\{ \int_{\alpha}^{\gamma} f_1(x) \, dx + \int_{\gamma}^{\beta} f_2(x) \, dx \right\}$$ \hspace{1cm} (3.5)

A problem is said to have an optimal substructure if an optimal solution can be constructed
Figure 3.5: Efficiency curves of two energy harvesting sister-circuits, for LPD and HPD.

Efficiency (%)

Received RF Power (dBm)

\[ f_1(x) \quad f_2(x) \]

\[ \alpha \quad \gamma \quad \beta \]

Efficiency curves of two energy harvesting sister-circuits, for LPD and HPD efficiently from optimal solutions to its sub-problems. We claim that this optimization also exhibits the optimal substructure property. The proof is presented as follows:

**Lemma:**

\[
\int_\alpha^\gamma f_1(x) \, dx + \int_\gamma^\beta f_2(x) \, dx
\]

is maximum then \( \int_\alpha^\gamma f_1(x) \, dx \) and \( \int_\gamma^\beta f_2(x) \, dx \)

are maximum as well.  \hspace{1cm} (3.6)

**Proof:** If \( \int_\alpha^\gamma f_1(x) \, dx \) and \( \int_\gamma^\beta f_2(x) \, dx \) were not maximum, then we could substitute \( \int_\alpha^\gamma f_1(x) \, dx \)

and \( \int_\gamma^\beta f_2(x) \, dx \) with larger values and hence obtain an even larger total area, \( \int_\alpha^\gamma f_1(x) \, dx + \int_\gamma^\beta f_2(x) \, dx \).

Furthermore, the efficiency curve is also a function of impedance matching network, consisting of inductor (\( L \)) and capacitor (\( C \)). This implies that for each particular crossover point, there exists more than one efficiency curve. It can be represented in mathematical form as follows:

\[ \forall \alpha : f(x) = f(L, C) \]  \hspace{1cm} (3.7)
Consequently, the equation 3.5 becomes,

\[ \gamma = \arg \max_\gamma \{ \int_\alpha^\gamma f_1(L, C, x) \, dx + \int_\gamma^\beta f_2(L, C, x) \, dx \} \]  

(3.8)

Finally, the number of rectifier stages influences the minimum required voltage at the input in order to obtain a certain output sufficient to drive a sensor mote. We consider various number of rectifier stages \( N \), ranging from 1 to 12 stages in this optimization framework. Hence, the equation 3.8 becomes,

\[ \gamma = \arg \max_\gamma \{ \int_\alpha^\gamma f_1(N_1, L, C, x) \, dx + \int_\gamma^\beta f_2(N_2, L, C, x) \, dx \} \]  

(3.9)

We can construct the general optimization framework as follows:

\textit{Given} : \( L, C, N \)

\textit{To find} : \( \alpha, N_1, N_2 \)  

(3.10)

\textit{To Maximize} :

\[ \text{Area}_{\text{total}} = \int_\alpha^\gamma f_1(N_1, L, C, x) \, dx + \int_\gamma^\beta f_2(N_2, L, C, x) \, dx \]  

(3.11)

\textit{Subject to} :

\[ \int_\alpha^\gamma f_1(N_1, L, C, x) \, dx > \int_\gamma^\beta f_1(N_1, L, C, x) \, dx \text{ and} \]

\[ \int_\gamma^\beta f_2(N_2, L, C, x) \, dx > \int_\alpha^\gamma f_2(N_2, L, C, x) \, dx \]  

(3.12)

\[ \forall x : I(x + \Delta x) \geq I(x) \]  

(3.13)

\[ \forall x : V(x + \Delta x) \geq V(x) \]  

(3.14)

\[ V(x = -10) \geq 1.8 \text{ V.} \]  

(3.15)

The aim of this optimization framework is to maximize area under the joint efficiency curve throughout, subject to several constraints which are explained below:

- The efficiency curves of both circuits, one optimized for low input power operation, i.e., the LPD, and another for high-power operation, i.e. HPD, should not overlap completely as the effective operational range of the circuit will be adversely impacted. This is possible by enforcing the constraint on having majority of the area under the efficiency curve to the left
of the crossover point for the LPD circuit, while HPD circuit has majority of the area to the right of the crossover point.

- Voltage and current should be monotonically increasing. This places a constraint on the efficiency curve of the energy harvesting circuit to be continuous and without sudden breaks.

- Finally, the output voltage at $-20 \text{ dBm} \geq 1.8 \text{ V}$. This is to ensure that at the energy harvesting circuit is operable at the point where it is practically required to drive the sensor mote in the active state.

![Figure 3.6: Efficiency Comparison at 10.75 dBm for different sub-circuit stages](image)

**3.3 Simulation Results**

The energy harvesting circuit is simulated using Agilent Advanced Design System (ADS) software. We use the *harmonic balanced analysis* (a frequency domain method) in this work since our objective is to compute the steady state solution of a non-linear circuit. The alternate method, the so called *transient analysis* that is undertaken in the time domain is not used owing to the reason that it must collect sufficient samples for the highest frequency component. This involves significant memory and processing requirements. The ADS schematic for ideal LPD circuit is shown in Figure 3.7.

For the optimization framework, we vary the crossover point throughout the target range, each time evaluating if the overall efficiency is optimized. The number of energy harvesting stages is
Figure 3.7: The ADS schematic for ideal LPD circuit

Figure 3.8: Optimal efficiency comparison at different crossover varied from 1 to 12 for both LPD and HPD circuits. Moreover, components in the corresponding matching network are tuned to yield the maximum efficiency for a given choice of crossover point. We use the input power step size of 0.25 dBm in this thesis for fine grained analysis. In the first study, we keep the crossover point fixed and observe the resulting changes in the efficiency curves when the number of stages varies, as shown in Figure 3.6. We vary the number of stages from 5, 7 and 9 for the LPD, while HPD stages are 8, 10 and 12. The optimal choice of the circuit stages at a given crossover point is that which maximizes the overall efficiency $\eta_o$. The value of $\eta_o$, as well the conversion efficiency area for the two sister-circuits are shown in Table 3.1. For the LPD, the value of the area under the efficiency curve increases as the number of stages increases from 5 to 7. However, its peak efficiency reduces as additional stages are introduced. We observe that the optimal solution for the LPD is composed of 7-stages. Likewise, 10-stages are found to be best for the HPD. Consequently, the overall optimal solution, in the rage of −20 dBm to 20 dBm, consists of the pair of 7-stage LPD circuit and 10-stage HPD circuit.
Next, the behavior of the proposed circuit for three different crossover points of 5 dBm, 10.75 dBm and 15 dBm are plotted in Figure 3.8. The optimal solution at 5 dBm crossover point consists of the pair of 5-stage for the LPD circuit and 10-stages for the HPD circuit. Similarly, a 9-stage LPD circuit and 8-stage HPD circuit is the optimal solution set at 15 dBm crossover point. During the sweep of the crossover point from the lower input power end −20 dBm to upper end 20 dBm, we select the optimal solution as one that yields the maximum $\eta_o$. Table 3.2 shows the normalized $\eta_o$ for various crossover points.

Through an exhaustive search following the constraints of our optimization framework, we find that the 7-stage low-LPD circuit and the 10-stage HPD circuit, with the crossover point of 10.75 dBm, yields the maximum $\eta_o$, and hence, this is the optimal solution to the framework. The efficiency curves and the subsequent normalized area values are included in Figure 3.9 and Table 3.2 respectively.

<table>
<thead>
<tr>
<th>Sub-circuit</th>
<th>Number of stages/Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPD</td>
<td>5-stage/1508.589</td>
</tr>
<tr>
<td></td>
<td>7-stage/1550.420</td>
</tr>
<tr>
<td></td>
<td>9-stage/1507.892</td>
</tr>
<tr>
<td>HPD</td>
<td>8-stage/722.535</td>
</tr>
<tr>
<td></td>
<td>10-stage/745.355</td>
</tr>
<tr>
<td></td>
<td>12-stage/745.222</td>
</tr>
</tbody>
</table>

Table 3.1: Normalized area at 10.75 dBm crossover point

In order to show the benefit of the proposed dual-stage design, we compare our design with Intel research’s Wireless Identification and Sensing Platform (WISP) [55]. WISP power harvester consists of a 4 stage charge pump and it employs Agilent HSMS-285C schottky diodes which is similar to that of our design. We use schematic and components’ parameters as published in [55]. Consequently, it is fair to say that the performance difference is the result of the design and optimization. Note that WISP uses the zener diode, connected in shunt configuration with the load, to regulate the output voltage. For this performance evaluation purpose, it is omitted from the simulation. Figure 3.9 shows the efficiency plots of WISP and dual-stage design. It is clear that the dual-stage design yields much higher efficiency at −12 dBm onwards. The benefit of dual-stage design stands out in HPD region where the efficiency of WISP drastically drops. However, WISP outperforms the dual-stage design between −20 dBm to −13 dBm. This is not surprising since we optimized the design to deliver optimal efficiency throughout the range of −20 dBm to 20 dBm.

The output voltage of the optimized energy harvesting circuit and WISP are shown in Figure 3.10. The energy harvesting circuit yields the output voltage of 2.074 V at −10 dBm. [19] has
stated earlier that the Mica2 sensor mote is able to operate at 1.8 V. This output voltage of energy harvesting circuit at $-10 \text{ dBm}$ is sufficient to fully operate the Mica2 sensor mote, once the energy storage is sufficiently charged. Moreover, at $-7 \text{ dBm}$, the output current of the energy harvesting circuit is $32.91 \mu A$. It implies that the energy harvesting circuit is able to directly supply the power to deep-sleep Mica2 sensor mote, on the basis that the energy storage is sufficiently charged, which requires no more than $30 \mu A$. The energy neutral operation can be sustained in the latter case.

### 3.4 Fabrication and Evaluation

The simulation results obtained previously are under an assumption that all components, except Schottky diodes, exhibit an ideal behavior. With non-ideal components and parasitic effects, this is rarely achievable in practice. Consequently, it is imperative that all related parasitic parameters and precise models of components have to be incorporated into the simulation. This not only yields a closer result to that of the prototype but also provides an upper bound on achievable efficiency with respect to a particular prototype design. For this purpose, Agilent ADS simulation with Co-Planar Waveguide with Ground Plane (CPWG) is used to observe the effect of the Printed Circuit Board (PCB). Moreover, components are modeled with ADS and vendor supplied component libraries. The voltage and efficiency comparison between ideal circuit and non-ideal circuit with PCB effect are shown in Figure 3.11 and Figure 3.12 respectively. The effect of non-ideal components and PCB becomes clear as the received RF input power goes beyond $-16 \text{ dBm}$. This implies that the fabrication method plays an important role on the performance of the energy harvesting circuit.
It is preferable to choose the fabrication method that yields the least parasitic effects as well as minimizes the effect of the components' layout. “System on Chip” (SoC) is a highly recommended fabrication method, which however lies beyond the scope of this thesis.

With the effect of non-ideal components and PCB, it is unlikely that one can achieve the optimal result obtained in the optimization section. We propose the use of multiple antennas in addition to the existing circuit. Consequently, the amount of energy harvested can be increased depending on number of antennas implemented. Figure 3.13 shows the energy harvesting with multiple input
antennas concept. Each antenna collects its own signal, connects to its own matching network and voltage multiplier. However, they all share the energy storage. Note that this concept does not increase conversion efficiency of the circuit since the efficiency of the circuit remains the same. However, the amount of harvested energy to area ratio is increased. The voltage and efficiency of circuits with multiple antennas are shown in Figure 3.14 and Figure 3.15 respectively. It is obvious that both voltage and efficiency of the circuit can be increased by introducing additional antennas. However, the gain increase is not linear and reduces drastically with additional antennas introduced. This limits the amount of multiple antennas used for the purpose of energy harvesting enhancement.

The final fabricated PCB of our proposed energy harvesting module connected to a Mica2 mote is shown in Figure 3.16. The PCB is fabricated with FR-4 epoxy glass substrate and has two layers, one of which serves as a ground plane. The prototype consists of the design obtained from the proposed optimization. We select components with values and ratings of their performance parameter as close as possible to ones obtained from the simulation. This data is summarized in Table 3.3

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor</td>
<td>3.0, 7.12 nH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>1.5, 2.9 pF</td>
</tr>
<tr>
<td>Stage capacitor</td>
<td>36 pF</td>
</tr>
<tr>
<td>Diode</td>
<td>HSMS-2852, HSMS-2822</td>
</tr>
</tbody>
</table>

Table 3.3: Components used in ADS simulation
The energy harvesting circuit prototype is tuned to match simulation parameters using Agilent E5061B vector network analyzer. In order to measure DC power output from the prototype, Agilent N5181 MXG RF signal generator is used to provide a known RF power to the prototype from $-20$ dBm to $20$ dBm. The DC output power from the prototype is obtained from measuring the voltage and current associated with the resistive load of $100$ KΩ. The load value representing the Mica2 is so chosen as it is measured in sleep mode to consume $30$ µA at $3.0$ V, which translates to
a 100 KΩ resistive load. We use Agilent 34401A multimeter to measure voltage and current on the resistive load. Our prototype is fabricated with specifications shown in Table 3.4.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminate thickness</td>
<td>62 mil FR-4</td>
</tr>
<tr>
<td>Number of Layers</td>
<td>2-layer, one serves as a ground plane</td>
</tr>
<tr>
<td>Copper thickness</td>
<td>1.7 mil</td>
</tr>
<tr>
<td>Trace width</td>
<td>20 mil with 12 mil gap</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>4.6</td>
</tr>
<tr>
<td>Through-hole size</td>
<td>29 mil</td>
</tr>
</tbody>
</table>

Table 3.4: Parameters used in PCB fabrication

We describe the efficiency of our fabricated harvesting board, also referred to as prototype, and compare with the commercially available RF energy harvester from Powercast [15]. We use P1100 evaluation board for the performance comparison. Powercast P1100 is a high efficiency RF energy harvesting device that converts received RF energy into DC power. The voltage and current of Powercast P1100 is measured with the same equipments under the same external conditions.

Figure 3.17 shows the voltage plot of the non-ideal simulation, prototype and Powercast P1100 across the load of 100 KΩ with −20 dBm to 20 dBm input RF power. It is clear that the voltage plots of the prototype, both LPD and HPD, are not able to exceed with the simulation results, though they both closely follow the voltage plots of the simulation with non-ideal components with PCB effect and exhibit similar behavior.

Figure 3.19 depicts comparison of output voltage plots of our prototype in LPD region against
Figure 3.16: RF energy harvesting circuit prototype

Figure 3.17: Output voltage comparison of simulation, prototype and Powercast energy harvesting circuit

the Powercast P1100 energy harvesting circuit. The proposed prototype provides a higher voltage than the Powercast P1100 throughout the range of $-20 \text{ dBm}$ to $20 \text{ dBm}$. At $-1 \text{ dBm}$, the output voltage of Powercast P1100 holds constant at 3.3 V. This is because the Powercast P1100 has the voltage regulator built into the package and it starts to regulate its output voltage at $-1 \text{ dBm}$ with the voltage of 3.3 V.

Figure 3.18 shows the efficiency comparison of non-ideal simulation, prototype and Powercast P1100 across the load of $100 \text{ K}\Omega$ with $-20 \text{ dBm}$ to $20 \text{ dBm}$ input RF power. In order to measure
the efficiency of the Powercast P1100 beyond −1 dBm, the output voltage of the Powercast P1100 is controlled under 3.3 V by varying amount of current drawn by the load. The efficiency plots precisely correspond to the voltage plots described previously. The efficiency plots of the prototype exhibit similar behavior when compared to non-ideal simulation values, except in the limited range of input power in which the LPD shows a comparatively high deviation between simulation and experimental results. This occurs owing to the inability of capturing parasitic capacitances, resulting from PCB manufacturing and components’ tolerance.

It is interesting to investigate feasible applications under extremely low power range, −20 dBm to 0 dBm. The prototype gives the output voltage of 1 V at −10 dBm and 1.9234 V at −6 dBm, respectively. At these two particular points, the prototype has the efficiency of 10% and 14.73% which are 10 µW and 37 µW, respectively. With the advancement in extremely low power Microcontroller (MCU), the power consumption continues to decrease. For example, Texas Instruments’ MSP430L092 can operate at the voltage as low as 0.9 V and consumes 3 µA in LPM4 mode, which translates to 2.7 µW. Consequently, the prototype can directly supply power to sustain the operation of MSP430L092 at as low as −10 dBm received RF power. Similarly, Mica2 sensor node is able to operate in power-down mode at −6 dBm received RF power.

The application is not only limited to powering sensors directly but also trigger charging, energy neutral operation and radio wakeup. In trigger charging operation, the surplus energy beyond sensor’s consumption is accumulated in energy storage, i.e. super capacitor and rechargeable battery, thus increases the sensor’s lifetime. For example, Texas Instruments’ MSP430G2553 in LPM4 mode draws 100 nA at 1.8 V, which translates to 180 nW. The prototype yields 2.5%
efficiency at $-20$ dBm, which is 250 $nW$. In energy neutral operation which the rate of energy consumption is less than or equal to that of the harvesting, the prototype is able to sustain the energy neutral of MSP430G2553 in LPM4 at $-20$ dBm. Finally, the energy harvesting circuit can be used to wake up the sensor node when predetermined signal strength is detected in the proximity. In this case, the sensor node has its own power source and spends most of the time in power-down mode. As a result, the sensor’s lifetime is extended with the use of energy harvesting radio wakeup.

With most applications the output power needs to be regulated. However, voltage regulation may not be of concern under some circumstances. For example, the high voltage produced by the circuit occurs under the assumption that the sensor is in power-down mode. Once the sensor wakes up, it draws higher current thus the voltage decreases. With ambient RF energy harvesting, the input voltage range is limited by the ambient RF, which rarely exceeds 0 dBm. So it is safe to say the output voltage is bounded and voltage regulator is not necessary. However, using a voltage regulator to regulate the output to a useful voltage is recommended for most applications. A simple zener diode, in shunt configuration with the load, can be used to regulate the output voltage similar to WISP design. Otherwise, a buck converter with large conversion ratio can be used for this purpose.
3.5 Section Summary

We show that with a simple yet optimal design and optimization, the prototype can yield almost double the efficiency than that of a major commercially available energy harvesting circuit in the low incident power range (simulation results for the circuit reveal about 70% operational efficiency). Our study implies that Mica2 sensor motes can be perpetually operated when their duty-cycle is carefully selected based on the incident RF power (as low as $-6 \text{ dBm}$). Moreover, the prototype is able to sustain the energy neutral of Texas Instruments’ MSP430G2553 in LPM4 at $-20 \text{ dBm}$. The experimental results are in good agreement with the values seen in the non-ideal simulation. We also compare our prototype’s efficiency with the commercially available RF energy harvester from Powercast, where our prototype largely outperforms the Powercast P1100 in the range of $-20 \text{ dBm}$ to $7 \text{ dBm}$. Finally, in order to have a performance improved at the lower cost, the circuit needs to be implemented as “System on Chip” [58] as it suffers less above mentioned parasitics, and we will pursue this in our future work.
Chapter 4

Device Characterization and Cross-layer Protocol Design

In this chapter, we present two flavors of cross-layer protocols, Device-agnostic (DA) and Device-specific (DS). These protocols determine the routing paths and the harvesting transmission duty cycle at each hop under different conditions: The DA scheme relies purely on the local measurements on the harvesting capability of a node after the sensors are deployed, and is useful for single-flow networks. The DS scheme provides a joint hardware-software optimization by allowing the selection of the energy storing capacitor, apart from the route and duty cycle determination. Both the schemes rely on a rich set of device-level experimental studies that help provide exact performance characteristics in practical scenarios. Consequently, the need of experimental studies which are presented below.

4.1 Device-agnostic (DA) Protocol

We describe the proposed DA scheme by first mapping the charging time of the energy harvesting circuit to the distance of the energy transmitter (ET). Then, we present the route formation scheme that uses the charging capability of a sensor as the metric. Finally, the duty cycle at the link layer is chosen for the nodes in the path through a linear optimization.
4.1.1 Relationship of charging time and distance

In this section, we determine experimentally the charging time for a given commercially available wireless energy transfer device, by the following steps:

Experimental Setup

Our experimental apparatus consists of a P2100 energy harvesting module from Powercast Co. [15], which operates in the 900 MHz ISM band, and is composed of an energy transmitter (ET) and receiver boards. The receiver converts the energy of the transmitted continuous wave 3 W signal sent by the ET to DC voltage with the help of a 1mF capacitor. This stored energy in the capacitor can then be used to re-charge standard batteries as the load, or directly for sensor operation. We compared the charging rates of the capacitor from $0 - 1.16 \text{ V}$, with the latter being a hardware enforced upper limit, for different transmitter-receiver separation distances in the range $[1.5, 12]$ meters. The experiments were conducted in a long corridor of our research building that simulated a tunnel-like behavior. Moreover, at each chosen distance, three different relative heights between the ET and the receiver we chosen as follows: (i) same height, (ii) receiver 0.5 m higher than ET, and (iii) receiver 1.5 m higher than ET, respectively.
Observations

The results of our experiments are shown in Figure 4.1 with the time for charging on the Y-axis, and the separation distance on the X-axis. Firstly, as a limiting condition, we observed that at distances greater than 12 m, the charging takes an infinite length of time, since the capacitor does not get to the maximum charge voltage at all. Thus, we assume this distance as the upper limit for the current type of energy transferring devices. Irrespective of the relative heights between the ET and the receiver, the general trend is towards an increasing charging time with distance. Interestingly, for 1.5 m height difference, there is considerable fluctuation at closer distances. The reason for this is the reflection of the EM waves from the ceiling (as the receiver is placed closer to the ceiling), and peculiar behavior of propagation loss inside a tunnel [59]. This result gives the non-intuitive message that even if a sensor is situated at a greater distance than others, depending upon the location-specific channel behavior, it may still exhibit a better charging rate (e.g. at the distances of 4.5 and 7 m for all the three heights). Note that for different hardware, these times will differ, and with improvements in RF transfer efficiency, the charging times can be significantly improved that can positively affect the network design. We use our experimental findings as a guideline to develop routing and link layer adaptation at the sensor networks using a similar RF transfer apparatus, as described in the next sections.

4.1.2 Charging-aware route formation

From our experiments, we observed that the charging rate for a given receiver is highly dependent on its specific location and relative height difference with respect to the energy transmitter ET. Thus, classical metrics such as shortest path, in which all nodes are considered to exhibit a homogenous charging characteristic, do not work well in a realistic setting. Moreover, the residual energy at a sensor may vary during the transmission and re-charging process, and hence this too cannot be static metric during route formation. The steps of our routing protocol are given as follows:

4.1.3 Route Establishment Metric

We propose using the charging time (4.1), measured as the time taken to reach the hardware limited voltage of 1.16 v as the decision metric, as opposed to [37]. First, there is an initialization phase, before the start of the network operation. The ETs transmit continuously for a pre-determined duration, allowing each sensor i to measure its own charging time, t_{ch}^i, and the standard deviation \eta_{ch}^i over multiple trials.
The route formation is initiated by the source node, and our proposed metric can be combined with most existing routing protocols for WSNs. In the current implementation, we modify AODV by including the tuple \(<T_{ch}^{max}(k), \eta_{ch}^{max}(k)\>\) in the route request (RREQ) packet that travels over path \(k\). Here, \(T_{ch}^{max}(k)\) represents the maximum charging time considering all the nodes currently traversed in the path \(k\), and \(\eta_{ch}^{max}(k)\) is the observed standard deviation for this maximum value. As the RREQ is forwarded by the sensors, they may update the field \(T_{ch}^{max}(k)\) if their own charging time is greater than the value contained in this field. Thus, for a sensor \(i\), the change \(T_{ch}^{max}(k) = t_{ch}^i\) if \(t_{ch}^i > T_{ch}^{max}(k)\), is undertaken before broadcasting the RREQ to its neighbors. In addition, the deviation \(\eta_{ch}^{max}(k)\) is also included in the packet, whenever the \(T_{ch}^{max}(k)\) changes, to resolve the ties at the destination.

To ensure that the best routes deliver the RREQs first, each node introduces a forwarding delay as a function of its own charging rate. This delay is computed as \(t_{ch}^i + \eta_{ch}^i\), i.e. the sum of the mean charging time and its deviation of the node divided by a constant factor (e.g. 1000 for delay in the order of ms). It is possible that the best RREQ, one with the lowest charging time, might not be guaranteed to arrive before the destination node sends out RREP. This is especially true in the case of multiple paths with different numbers of hops. In order to alleviate this issue, the DA scheme has the mechanism that is adaptive to achieve the optimal route, i.e., it keeps track of the best RREQ received and updates the route when necessary, i.e. the destination node sends the new RREP if it receives RREQ with the lower charging time. This occurs as DA is built atop the classical AODV that incorporates this feature in by default. This enables the route to sustain its optimality in the DA scheme.

The destination receives multiples RREQs representing the different paths traversed from the source. It now chooses the path, say \(\psi\), with the lowest value of the maximum charging times of the various paths. Thus,

\[
\psi = \min\{T_{ch}^{max}(k)\} \forall k
\]

\[
= \min\{\max[t_{ch}^i]\} \forall i \in \text{path } k, \forall k,
\]

(4.1)

The destination waits for a time \(T_{setup}\) during the route formation and collects multiple RREQs. Shorter charging times also imply more opportunity for packet transmission, and results in greater throughput. The per-hop delay incurred in the few additional hops in the chosen path is easily offset by the gains in increased network lifetime, as we show in Section 4.1.1.

In practice, the charging time might be affected by many factors, i.e. mobility, fading. This is particularly true in the mobile WSN with ambient RF energy harvesting. However, the charging time of the system of interest is less exposed to such variations, i.e., energy harvesting mobile
WSN powered by dedicated energy transmitters. As with any routing protocols, the DA scheme captures the system state then performs the optimization on the collected data. There is insignificant difference whether the system is dynamic or static since the routing protocol has to make a decision on the instantaneous system state. So it is fair to say that the setup route and duty cycle are optimal with respect to the present state. In order to capture the dynamic of the system, the DA protocol has an adaptive mechanism to deal with the dynamic nature of the system. The adaptive mechanism includes a feature called route invalid masking, which deletes the route if it is non-active. Route invalid masking in the DA algorithm keeps track of active routes and marks ones that are non-active, i.e., each node determines whether its neighbor is considered active for the particular destination. The neighbor of the node is considered active for a particular destination if the neighbor sends a packet or forwards at least one packet for a destination within the active route timeout interval. The charging time deviation during the route setup also has an influence on route expiration since it reflects the dynamic of the system. In the next section, we demonstrate how the charging and transmission durations are optimally decided for the selected path while considering several end-to-end performance metrics.

4.1.4 Charging and transmission time optimization

After the base station chooses the optimal path, it sends back the route reply (RREP) to the nodes of this path, defining the charging \( T_{ch} \) and transmission times \( T_x \) that is common to all of them. Thus, even if a node \( i \) advertised a different value for \( t_{ch}^i \) to charge fully, it must now cease transmission and stay in the charging phase for the entire length specified by \( T_{ch} \). Our optimization framework given below returns the duration for charging \( T_{ch} \) and the frame length \( T_{frame} \), where \( T_{frame} = T_{ch} + T_x \). Once the RREP reaches the source in the return path, all the nodes are initialized and the network can now begin forwarding the data packets.
Given: \( L_{\text{lim}}, ESR_{\text{lim}}, N \)

To find: \( T_{\text{ch}}, T_{\text{frame}} \)  

(4.2)

To Maximize: \( \text{Throughput} = \frac{T_x \cdot R}{T_{\text{frame}}} \)

Subject to:

\[
(\text{E}_{\text{rec}} - \text{E}_{\text{idle}}) \cdot T_{\text{ch}} - \text{E}_{\text{tx}} \cdot T_x \geq 0 \tag{4.3}
\]

\[
N \left( T_{\text{ch}} + \frac{P + H}{R} \right) \leq L_{\text{lim}} \tag{4.4}
\]

\[
\frac{1}{ESR_0} \left[ 1 - k \cdot t \cdot \exp^{\frac{-4730}{T + 273}} \right] > \frac{1}{ESR_{\text{lim}}} \tag{4.5}
\]

\[
T_{\text{frame}} = T_x + T_{\text{ch}} \tag{4.6}
\]

The aim of this optimization framework is to maximize the throughput subject to several constraints. As the node can only transmit during the transmission times, and must remain silent during the charging times, the throughput is expressed as the ratio of total number of bits sent during \( T_x \) to the frame time \( T_{\text{frame}} \). The end-to-end latency limit \( L_{\text{lim}} \) and the capacitor quality metric \( ESR_{\text{lim}} \) are specified based on application and device lifetime requirements. Finally, \( N \) is the total number of nodes in the path. In order to find the charging time \( T_{\text{ch}} \) and the frame time \( T_{\text{frame}} \) that maximizes the throughput, we define the constraints as follows:

- The constraint of keeping the sensor alive after each frame duration is reflected in (4.3). Here, the sensor expends idle energy \( \text{E}_{\text{idle}} \) during its charging time. This is a function of the internal circuit operation of the sensor. However, it gains energy at the rate \( \text{E}_{\text{rec}} \) from the wireless transmitter in this duration \( T_{\text{ch}} \). In addition, during the transmission duration the sensor looses energy at the rate \( \text{E}_{\text{tx}} \) due to sending and receiving packets. Thus, after the frame duration, the residual energy must at least be greater than 0.

- The end-to-end latency of a packet for the \( N \) hop route must be below a pre-decided limit \( L_{\text{lim}} \) as given in (4.4). This can be function of the type of application and the nature of the data expected from the network. At each hop, in the worst case, a sensor may experience a delay equal to the charging time \( T_{\text{ch}} \) in which no data can be sent and the transmission delay which is given by the ratio of the packet size \( P \) combined with the header size \( H \) and the sending rate \( R \).
• Equivalent series resistance (ESR) is a metric that is used to determine the operational quality of the capacitor. Over time, the ESR increases, and once it is beyond the limit $ESR_{lim}$, the capacitor is considered dysfunctional. The capacitor lifetime constraint is captured in \((4.5)\), where $T$ is the absolute temperature in Kelvin at which the capacitor operates, $t$ is the operational time, and $k$ is a design constant. The capacitor is subjected to a charging voltage only during the interval $T_{ch}$ in each frame. Thus, if $\mu$ is the target network lifetime in terms of number of completed frames, then the effective operational time of the capacitor is $t = \mu \cdot T_{ch}$.

• Finally, the constraint \((4.6)\) gives the relationship between the charging and transmission times and the frame time.

### 4.2 Device-specific Protocol

In the device-specific (DS) approach, we model the integrated energy harvesting module and sensor mote (as shown in Figure 1.2) through precisely constructed equations as part of the device characterization. These equations exactly state the capacitor voltage (hence, residual energy) during the energy harvesting and sensor transmission durations, which are obtained from the determination of the link layer duty cycles. Finally, the routing protocol helps in choosing the best route among the candidate paths.

#### 4.2.1 Device characterization

We undertake this study in two steps, i.e., develop analytical models for the charging and operational phases of the sensor.

**Charging Phase**

We obtain the relationship between the received power $P$, the capacitor $C$ that will be charged by the energy harvesting device, and the output voltage $V$ up to which the capacitor can be charged through real measurements of our energy harvesting equipped sensor. The classical approach of using the power and voltage relationship of the capacitor, i.e., $V = V_o(1 - e^{-\frac{t}{RC}})$ cannot be directly applied to obtain the charging time $t$. This is because the harvesting circuit is composed of non-linear and reactive components (Schottky diodes, inductors and capacitors) whose efficiency and reactance vary with the incident signal or power level. Several additional circuit enhancements exist, such as dynamically switching between multiple stages of the basic voltage multiplier circuit.
which cannot be obtained from a simple study of the circuit. Moreover, our multivariable function allows the network designer the flexibility in choosing the energy storage capacitor based on application environments.

We used the Powercast P2100 as the energy harvesting device and Agilent Technologies N5181A signal generator to feed in varying signal power levels from $-20$ dBm to 17dBm. We also varied the storage capacitor size from $1\mu F$ to $220mF$, and measured the time taken to charge to the maximum voltage output from the harvesting module (3.3V). For each capacitor size, the voltage-time curve was logged for varying input power levels. We begin with the equation

$$V = a_1e^{a_2t} + a_3e^{a_4t},$$

which gives the voltage at the capacitor when the harvesting circuit is in use for time $t$, all other node operations being suspended. We base this choice by implementing a family of different functional approximations in MATLAB, and testing for the least square error (MSE) criterion. Interestingly, $a_1$ and $a_3$ turned out to be constant with the variation of $P$, but the terms $a_2$ and $a_4$ were exponential functions themselves for the best fit using the LSE criterion. Coefficients $a_1, a_3, a_4$ and $a_6$ did not show any changes with respect to $C$ in the curve fitting process, and were kept constant. However, coefficients $a_2$ and $a_5$ were inversely proportional to $C$. Hence, the final form of the equation is given in (4.7).

$$V = f(P, C, t) = a_1e^{a_2t} + a_3e^{a_4t}$$

From (4.7) and using Gauss-Newton optimization method [60], an approximation of coefficients $a_i$ were calculated as \{32.62, 2.38e$-5$, 0.23, $-30.86$, 2.35e$-5$, 0.23\}, respectively, for $i = 1, \ldots, 6$. The functional representation of the charging phase is shown in Figure 4.2(a).
Operational phase

Power consumption of the sensor is different during transmission and reception. Additionally, since the storage capacitor that powers the node during its operation is not a fixed voltage source, the voltage across it drops until it reaches a point, here 1.8V, where the sensor stops operating. Figure 4.2(b) shows the voltage level drop on a 100 mF capacitor versus time, consumed by a Mica2 mote for transmission-only (at −20 dBm) and reception-only modes.

To characterize the energy loss during transmission, two Mica2 sensor motes running TinyOS 2.1.0 were used as a sender-receiver pair. The transmitting mote used only the stored energy in the capacitor. The packets contained the the source node ID, time-stamp, sequence number, and voltage level the sender’s capacitor, and were continuously sent till the node shut down because of energy depletion. Figure 4.3 illustrates the discharging characteristic of the sender node under 3 different capacitor sizes (82mF, 100mF, 220mF). At the receiver side, a similar study was undertaken, where the mote was powered only from the charged capacitor and programmed to receive packets until the shut down voltage 1.85 V was reached. Then, all the received packets are written to the non-volatile EEPROM memory before shutting down. At the next bootup, the sensor transfers these packets to the host computer via a base station. Using these measurements, we estimate the residual time to energy depletion of a node due to reception ($T_{rx}$) and transmission ($T_{tx}$) alone, respectively, as follows:

$$T_{rx}(C, V) = -13 - 87.5C + 9.3V + 47.7CV - 1.3V^2 \quad (4.8)$$

$$T_{tx}(C, V) = -17.3 - 60.8C + 12.2V + 34.7CV - 1.5V^2 \quad (4.9)$$
4.2.2 Link layer duty cycles

In this section, we calculate the charging time $T_{ch}$ and the transmission time $T_x$ that are used by all the nodes of the network.

First, each sensor undertakes a one-time reporting of the level of received power (say, from the external energy transmitter) to the base station. If direct feedback is infeasible, which is possible for very large networks, then the average received power at each node can be calculated, by knowing the transmitter locations and using an appropriate path loss model. Figure 4.4 shows the analytically calculated probability density function (PDF) $P$ of the received harvesting power in a network of 30000 nodes in a 300 $\times$ 300 area where a 10 $\times$ 10 grid of 3 W energy transmitters is present.

Next, we formulate a framework that finds the best values for the storage capacitor value $C$ and the voltage $V$ up to which the capacitor must be recharged, so that the useful transmission time is optimized. Thus, we can formally express this calculation as:

$$\{C, V\} = \arg_{C, V} \max \int_{P_{min}}^{P_{max}} \frac{P(T_x(C, V) + T_{ch}(C, V))}{f'(P, C, V)} dP$$  \quad (4.10)
Figure 4.5: The effect of non-optimal capacitor size and voltage on the duty cycle of the DS protocol.

The above equation is derived from (4.7) and (4.9), which respectively denote the charging time, and useful transmission time, respectively. The transmission time itself can be equally used between packet sending and receiving at a given node, and hence, we take the average residual time accounting for both of these factors. Moreover, as the received power itself is not a constant for all nodes, we consider a range of values given by the PDF $\mathbb{P}$ under the boundary conditions of minimum ($P_{\text{min}}$) and maximum ($P_{\text{max}}$) received powers, respectively. Finally, $T_{ch} = f'$ is the inverse of $f$, and it gives the time taken to charge the capacitor to the upper limit of 3.3 V. This inverse is computed numerically from (4.7) using MATLAB.

Solving the above equation for the same sample scenario used to generate the PDF in Figure 4.4, we get $\{C, V\} = \{0.02 F, 3.0 V\}$. These values, in turn, result in $T_{ch} = 628.2$ and $T_x = 1.97$ seconds, respectively.

The result from the optimization are the optimal capacitor size and the charging voltage. This implies that the sensor will operate with the optimal duty cycle if these parameters are in effect. However, it is important to observe the effect of deviation in capacitor size and charging voltage on the duty cycle. Consequently, the capacitor size and charging voltage are varied to observed the duty cycle. Figure 4.5 shows the duty cycle under various capacitor size and charging voltage. It is obvious that the duty cycle is maximized at the capacitor size of 20 mF and the charging voltage of 3.0 V, which derived from the optimization mentioned earlier. Note that 20 mF is the lowest capacitor size that renders Mica2 operational in practice. It is also clear that changes in parameters do not significantly affect the duty cycle rather than yielding sub-optimal duty cycle.
4.2.3 Routing protocol

In the previous section, $T_x$ was chosen for the entire network. However, nodes with receive power levels significantly lower than the average given by the distribution of $P$ are likely to run out of energy before this duration $T_x$ is completed.

In order to decide a node’s suitability to participate in the route, we measure the time actually left for the node’s operational phase (based on the residual energy and node-specific conditions). Formally, this actual time for transmission, called as the **active time** $A_i$ for the node $i$ is,

$$A_i = \min\{T_x, \frac{T_{rx}(\mathcal{C}, \mathcal{V}) + T_{tx}(\mathcal{C}, \mathcal{V})}{2}\}$$  (4.11)

We assume here that a node spends equal time receiving and sending packets. A node with higher active time is preferred to forward the packet among potential relay nodes. Note that $T_{rx}(\mathcal{C}, \mathcal{V})$ and $T_{tx}(\mathcal{C}, \mathcal{V})$ are calculated based on the values derived in Section 4.2 for $\mathcal{C}$ and $\mathcal{V}$, respectively.

The source sends out a modified route request (RREQ) packet during route formation. Each sensor may forward the RREQ only if the active time is sufficient to transmit a data packet of length $L$ under a pre-determined rate $R$. Hence, the packet is forwarded if $A_i \geq \frac{L}{R} + \psi$, where $\psi$ is the average observed MAC layer channel access delay, and $\frac{L}{R}$ is the packet transmission time. This step is shown in the first conditional test block in Figure 4.6. Further, the RREQ has two additional fields given by the tuple $<\text{Time}, \text{FrameN}>$. $\text{Time}$ contains the cumulative time that the data packet will take to traverse the path in a given frame, where a frame is defined as the duration $T_{ch} + T_x$. The $\text{FrameN}$ field gives the total number of frames required to deliver the packet up to the given node. This is a key metric as the charging times $T_{ch}$ are indeed lengthy (hundreds of seconds), and these durations that render the sensor incapable of data forwarding, are present in every frame. If the first conditional test block is true, the node calculates the total delay in the current frame, i.e., the sum of the previous value of $\text{Time}$ and the current link delay $D$, defined as $\frac{L}{R} + \psi$. If this time is greater than the maximum possible active time, then the $\text{FrameN}$ count is incremented by one, indicating that the packet now needs to wait for the next transmission duration. In this case, $\text{Time}$ is reset to reflect the time elapsed in the current frame only.

The destination chooses the route that takes the minimum number of elapsed frames to deliver the packets, i.e., minimum value of $\text{FrameN}$. As the time of arrival of the RREQ does not reflect the final path chosen, each forwarding node, as well as the destination, must continue to accept RREQ packets even if an earlier one has already been processed for a pre-determined duration $\delta$. 


4.3 Performance Evaluation

In this section, we thoroughly evaluate our proposed approach using the ns-2 simulator. A total of 200 nodes were randomly deployed in a 100 × 100 m area. The sensors operate in the lowest power consumption state, using −20 dBm for transmission power to maximize their lifetimes. This, however, results in the tradeoff of 10 m operational range using the free space path loss model. Figure 4.7(a) shows the topology used in the study with the 3 W energy transmitters (ETs) arranged in a grid. The WSNs form chains with the source at one end and the sink located at the top right corner, and the total area of deployment is a square of side 100 m. The preliminary study on the DA scheme appeared in the shorter version of this thesis section [19]. However, we present completely new results and metrics that serve to compare the two approaches. Importantly, the energy model used is thoroughly revised based on actual measurements described in Sections 4.2.1 and 4.2.1, respectively. For the purpose of comparison, we have also implemented a voltage-aware AODV-based scheme (VA) [37], which was described in section 2.

4.3.1 Comparison of duty cycles

Consider a single diagonal route shown in Figure 4.7(a). Figure 4.7(b) shows the calculated duty cycle on this route using Device-Agnostic (DA) and Device-Specific (DS) schemes. The broken
A 12 × 12 energy transmitter grid and a chain of sensor nodes

Figure 4.7: Network topology and duty cycle comparison of various schemes

line shows the individual duty cycles calculated for the sensors along the 12-node path in the DS scheme. However, the DS scheme decides one network-wide fixed duty cycle, using the calculations in Section 4.2.2, which is shown by the solid line. This is the average value of the duty cycle for all the nodes within the network. Intuitively, the duty cycle in the DS scheme is much higher than that for the DA scheme, as the latter is decided by the duty cycle of the node having the longest charging time in the path (Section 4.1.4).

4.3.2 Effect of the number of energy transmitters

We vary the number of ETs deployed in the network in the range 9 × 9 to 12 × 12 arranged as a regular grid while keeping the area size constant. This increase in the number of ETs allows nodes to harvest more energy. Figures 4.8 and 4.9 show the effect of varying the ET grid size on the throughput and packet latency in 3 different schemes, including Device-Agnostic (DA), Device-Specific (DS) and Voltage-Aware (VA). The DS scheme delivers the highest throughput among these three, while the DA scheme yields the lowest throughput. The delay of DA scheme was considerably large in the order of tens of seconds (owing to very low duty cycles, as seen in Figure 4.7(b)) and was removed from the Figure 4.9 for the sake of visibility and comparison between the DS and VA schemes.
4.3.3 Effect of the network load

The rate of data packets loaded to the network, called as network load, was varied from 2.4 Kbps to 38.4 Kbps in this study. In Figure 4.10, we observe a distinct increasing trend for both DS and VA schemes, although DS performs better than VA. However we observe that the DA scheme not only yields significantly less throughput but also shows no major change in throughput with increasing load. This is because in the given optimization, the optimized charging time is calculated based on a signal rate and also to gain sufficient charge to send only one packet at a time. Figure 4.11 shows the latency comparison of the DS scheme against the VA. The DA latency is again not shown for the purpose of visibility, as it is much higher than both DS and VA. It is shown that the
VA yields a marginally lower latency than DS. However, the difference in latency decreases as the load produced increases. Moreover, at the highest load produced, both schemes yield insignificant difference in terms of latency. We believe that at the highest load produced, the network is saturated and the behavioral aspect of both DS and VA is overwhelmed by the limited data rate of Mica2’s radio, 38.4Kbps. In most applications where throughput is of most concern, the gain increase in throughput of the DS scheme over the VA scheme can easily offset the marginal latency introduced by DS.

![Figure 4.10: Throughput comparison of routing schemes with varying load from source node injected to the network.](image1.png)

![Figure 4.11: Latency comparison of routing schemes with varying load from source node injected to the network.](image2.png)
4.3.4 Effect of multiple flows

The effect of multiple simultaneous flows in the network was investigated, between randomly selected source nodes and destinations. We vary this number of flows from 1, 2, 4 and 8. Figures 4.12 and 4.13 show the effect of such variation on the throughput and average packet delay in the network. Recall that the DA scheme relies on the entire path having one duty cycle, and multiple flows that cross each other adversely affect the performance of the DA scheme. Hence, this study is focused on evaluating the performance of the DS and VA schemes. Figure 4.12 shows that throughput increases for DS scheme while the VA scheme does not show a major change with increasing number of flows. We interpret this behavior as follows: in the DS scheme, a path composed of nodes with high recharging ability are picked, therefore those nodes can serve more number of flows during their active transmission times. But since in the VA method, only the instantaneous voltage of nodes are used as routing metric, this does not represent their available voltage at later times when the nodes harvest the ambient energy. Hence, during the actual network operation, there is no observed correlation in the throughput with increasing number of flows for the VA scheme. The latency of DS and VA scheme is shown in 4.13. The DS scheme yields a minimally higher latency than the VA scheme. The difference in latency among both scheme is less pronounced as number of flows increases. We explain the phenomenon as follows: As number of flows increases, more nodes in one flow also belongs to other flows. This results in premature energy depletion of the nodes that participate in multiple flows.

![Figure 4.12: Throughput comparison of routing schemes with varying number of data flows](image)

In summary, we observe that in all the cases where throughput was studied, the DS method performs the best. This is because it chooses the path with lowest number of frames $Frame_N$, i.e., a path that delivers the packets to the destination as fast as possible.
4.4 Section Summary

We proposed two cross-layered protocols for Energy Harvesting Networks, Device-Agnostic (DA) and Device-Specific (DS). A thorough performance evaluation was conducted with various important metrics, including duty cycles, number of energy transmitters, network load and multiple flows. The duty cycle of DS scheme is much higher than that of DA scheme. In most applications where throughput is of most concern, the DS scheme is preferable over DA and VA scheme due to higher throughput yielded. The DS scheme also yield marginally higher latency than the VA scheme. However, the significantly higher throughput of the DA scheme can easily offset the marginal latency incurred. On the other hand, the lower latency of VA scheme makes it suitable for applications which the lowest latency is required. The lowest latency requirement becomes insignificant as the network converges to the saturation point, i.e. the data rate of the radio employed.
Chapter 5

Medium Access Control Protocol Design: RF-MAC

One of the important aspects of the RF-MAC protocol is to maximize the wireless energy transfer to the requesting node. We first demonstrate the effect of phase difference of energy transmitters’ signal, through the preliminary experiment, on the received signal at the receiver. The result from the preliminary experiment is then intuitively used to design the two-tone energy transfer in RF-MAC protocol.

5.1 Preliminary Experiments

In our experiments to characterize the constructive and destructive effect of the ETs, we placed two such 0 dBm continuous wave transmitters 2.5 m away from the receiver. Two Agilent N5181 MXG RF signal generators, each connected to a 50 Ω omnidirectional antenna tuned to the 915 MHz ISM band, were used to generate the signal. We fixed the phase of one signal generator and varied the phase of another signal generator, while keeping the their locations fixed (note that keeping the transmission phase fixed and varying their distance as a function of the signal wavelength will have the same effect on the received signal phase). The fall in the signal strength, shown in Figure 5.1(a), was dramatic when the ETs operated in phase opposition (−54 dBm) compared to in-phase operation (−36 dBm).

The bandwidth of the RF energy harvesting circuit connected to the sensor determines the maximum frequency separation of the continuous wave ETs, a desirable approach if the latter are in complete phase opposition. If the bandwidth of this circuit is narrow, or the spread of the
transmitted spectrum too large, there may not be enough room to completely separate the spectrum of the two transmitters by assigning them slightly varying center-frequencies. Hence, there may be an overlap in the two out-of-phase energy transmitters with a resulting destructive combination. Moreover, the bandwidth of the energy transmitter also has an effect on maximum energy transfer. It is preferable to have signal power contained in a narrow bandwidth, say within 99% of the occupied bandwidth. This relaxes the constraint of having a complete separation of out-of-phase signal bandwidth for different ETs.

Having established the need for separating out-of-phase ETs, we next direct our attention on how much of the phase mismatch is actually harmful. If the ETs are not completely $\pi$ radians separated in phase, then some of them may even be allowed to transmit together. The resultant increase in the raw emitted power in these cases compensates for the loss owing to the slight mismatch. Figure 5.2(a) shows the effect of phase difference $\delta \phi$ between two energy transmitters on the received signal power at 433 MHz and 915 MHz. This difference is varied from $[0, \pi]$ radians. A phase difference of 0 or $2\pi$ for the received signal (the emitted signals being in-phase) corresponds to a linear distance of one wavelength between the two transmitters. Thus, depending upon the actual distance $L$ between the ET $x$ and receiver node, we represent $\phi_x = \frac{L}{\lambda} \cdot 2\pi$. Here, $\lambda$ is the wavelength of the transmitted radiation. From Figure 5.2(a), we observe that for small phase difference, i.e., for $\Delta \phi \leq \frac{\pi}{2}$, the resultant signal signal strength is not significantly lowered (i.e., the fall is only about $1 - 2$ dBm). Hence, we group together all those ETs that are separated

**Figure 5.1:** Effect of phase difference on single tone and power spectrum of *two-tone*
by $\Delta \phi \leq \frac{\pi}{2}$ under one category (and center its transmissions at frequency $f_1$, say). Similarly, ETs that are separated by $\frac{\pi}{2} \leq \Delta \phi \leq \pi$ fall in the second category (and use frequency $f_2$ as the center transmission). We call this method as the two-tone energy transfer.

In Figure 5.2(b), using the discussion above on the relationship between the phase and distance, all ETs separated by a multiple of the wavelength from each other, i.e., $L = m\lambda$, $m = 1, 2, \ldots$ transmit on $f_1$, while the others separated by $L = (m + 1/2)\lambda$ transmit on frequency $f_2$. As there are two active transmission tones present concurrently during transmission, each of these are separated in the frequency domain, one on each side of the center response point of the harvesting circuit. Both these tones must be completely encompassed by the response of the harvesting circuit at the receiver side. Clearly, the EH circuit with a wide and flat frequency response accommodates better separation of transmitting frequencies. Our detailed investigations on the design of such a RF energy harvesting circuit are described in [14], where we design the circuit to deliver the highest power at the tuned frequency of 900 MHz. However, the output power begins to drop if there is any deviation from the tuned frequency, depending upon component selection and normal wear and tear of continuous operation. We measured the reduction in circuit efficiency within a frequency span of 10 MHz on either side of 900 MHz and observed that the reduction is approximately 0.38%. As opposed to this, the 99% occupied bandwidth of the Powercaster transmitter is relatively small, approximately 63 kHz, thereby allowing us to accommodate the entire transmission spectrum of the ET within the frequency response curve of the EH circuit.
5.2 RF-MAC Protocol Description

In this section, we describe the three main steps of our RF-MAC protocol using, namely (i) energy transmitter selection (ii) adaptive charging threshold selection, and (iii) access priority.

5.2.1 Overview

A brief summary of the protocol operation is shown in Figure 5.4, where three sensors S1, S2, and S3 have residual voltages of 2.6, 2.3, and 3.0 v, respectively. Recall that energy contained within a capacitor of value $C$ and the voltage across its terminals are related as $E_{res} = \frac{1}{2}CV^2$. When the voltage falls below a pre-set threshold (\sim 2.3v, as minimum operating voltage of the Mica2 is 1.8v), the node sends out the RFE packet, requesting for energy. Hence, $S2$ is in need of immediate charging. RF-MAC, through the access priority mechanism (Section 5.2.4), ensures that $S2$ wins the channel access for energy transfer earlier than $S1$ and $S3$ that have data packets to deliver. In the energy transmitter selection step that follows, node $S2$ sends out the RFE, identifies the set of ETs, and separates them into two groups with non-overlapping spectrum within the transmission band (Section 5.2.2). At this time, $S1$ and $S3$ are also forced to freeze their backoff timers and get into charging mode, as data communication is infeasible at this time. How much should $S2$ charge (i.e., the duration for which data communication is disrupted) depends upon the adaptive charging threshold selection (Section 5.2.3). This threshold is unique for a given node, and is
Figure 5.4: Priority of channel access.

derived from the ratio of its own data communication activity to that observed in its neighborhood. Finally, when nodes $S_1$ and $S_3$ compete for data transfer, access priority ensures their respective backoff windows are a function of the residual energy (Section 5.2.4). Assuming that $S_1$ has higher residual energy, it will likely get the data communication opportunity first, followed by $S_3$. The latter freezes the countdown timer in this duration, and resumes the remaining countdown as soon as the channel is next available.

5.2.2 Energy transmitter selection

The RFE contains only the requesting sensor node’s ID, transmitted at a constant signal strength. This RFE can only be sent when the channel is free, i.e., when there is no ongoing data transfer or energy charging operation and the channel lies idle for the $DIFS_{\text{energy}}$ duration (calculation of this channel sensing duration is described later in Section 5.2.4). The ETs that receive this packet estimate roughly their distances from the node, based upon the received signal strength (RSS).

Recall from Section 5.1, the distance between the ET and the sensor node directly results in a phase difference for the incoming wireless signals at the node. The ETs that identify themselves to lie in the band $[m\lambda - \frac{\lambda}{4}, m\lambda + \frac{\lambda}{4}]$, are grouped together, where $m = \{1, 2, \ldots\}$. We call this as Group I. Similarly, the other ETs in the range $[(m+1/2)\lambda - \frac{\lambda}{4}, (m+1/2)\lambda + \frac{\lambda}{4}]$ fall in the second group, called Group II. Thus, on receiving the RFE, each ET knows which concentric band it lies in centered around the requesting node, and the group in which it belongs. Figure 5.3(a) shows a sample scenario. The shaded region depicts the ETs 4 and 5 that lie in the band of $\lambda$, i.e., in Group I. This region extends up to $\frac{3\lambda}{4}$ on either side of the central bold line that lies at an exact distance of $\lambda$ with the requesting node placed at the center. Since we do not precisely require the ET to calculate the distance from the requesting node, but only need to determine if it lies within a concentric band-region, our approach is more robust to RSS fluctuations. Of course, using a
dedicated localization scheme or GPS hardware considerably eases this constraint, though adding to the implementation cost and power requirement.

**Grouping of the responding ETs**

The ETs that hear the RFE reply back with a single, constant energy pulse. Each concentric band has the choice of one of two time slots in which this pulse may be emitted, beginning from the instant of completion of the RFE, as shown in Figure 5.3(b). Referring again to the band structure in Figure 5.3(a), the first slot is allocated for CFE pulses sent by energy transmitter of Group I (note: all Group I bands are shown shaded). Similarly, CFE pulses from energy transmitters of Group II are sent during the second slot, i.e. ETs 1, 2 and 3 collectively lie in the second concentric (Group II) band and simultaneously transmit their pulses in the second slot. The node that sent the initial RFE estimates the total energy that it will receive based on the signal strength of the CFE pulses in the slot number in which they were received. This arrangement of using the pulses allows the ETs to be simple in design, and removes the concern of collisions in the reply packet. Unlike classical data communication, it is not important for the node to know *which* ET will transmit energy. Rather, its energy calculations are based on *how much* energy is contributed by the two groups of ETs separately. We define this cumulative energy as $E_{Group \ I}^{RX}$ and $E_{Group \ II}^{RX}$, respectively, which are calculated by the RFE issuing node from the received pulses. Each slot time is 10 µs in our work, allowing a very fast response time.

The purpose of differentiating the energy contribution from the two groups is useful in the next stage, where an optimization function returns the center frequencies of the ETs. Let Group I ETs be centered at frequency $f_1$, and Group II ETs be centered at frequency $f_2$ so that they can concurrently transfer energy without destructively affecting each other. Also, a desirable goal is to have minimum separation $f_2 - f_2$, as the spectrum is most efficiently utilized. This also leaves open the possibility of future advancements using more than two concurrent frequencies. How to select these frequencies $f_1$ and $f_2$ is explained next, which takes into account two important physical layer characteristics of the energy transfer. The first is the spectrum response of the energy harvesting circuit that is connected to the sensor nodes, shown by the envelope $H(f)$ in the frequency domain in Figure 5.2(b). The power spectral density (PSD) of the two groups of ETs is the other concern, represented by $S_1(f)$ and $S_2(f)$, respectively, for Group I and Group II. These shapes are observed by the sensor node from the incoming pulses from the ETs. Thus, the bandwidth $2\varepsilon$ of the transmission spectrum (centered at $f_1$ and $f_2$) must be selected in such a way their is minimum overlap between their individual spectra, and yet contained within the envelope of $H(f)$ to affect the maximum level of power transfer. We use the following optimization assuming the transmission spectrum of the ETs occupies a bandwidth of $2\varepsilon$. 

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Optimization function for frequency assignment

The aim of the optimization formulation is to maximize the energy transfer $E_{RX}^{Max} = E_{RX}^{Group I} + E_{RX}^{Group II}$ to the requesting sensor node. The energy transferred by the RF signal at a given frequency point is the product of the power spectral density and the circuit frequency response, i.e., $S_1(f)H(f)$. Thus, the useful components that need to be maximized are the first two terms of (5.2), which give the constructive energy contribution of the ETs of the two groups.

Given: $S_1(f)$, $S_2(f)$, and $H(f)$

To find: $f_1$, $f_2$  

To Maximize:

$$E_{RX}^{Max} = \int_{f_1-\varepsilon}^{f_1+\varepsilon} S_1(f)H(f)\,df + \int_{f_2-\varepsilon}^{f_2+\varepsilon} S_2(f)H(f)\,df$$

$$- (\int_{f_2-\varepsilon}^{\gamma} S_2(f)H(f)\,df + \int_{\gamma}^{f_1+\varepsilon} S_1(f)H(f)\,df)$$

Subject to:

$$\left| \frac{d(S_1(f)H(f))}{df} \right|_{f=\gamma} < 0$$

$$\left| \frac{d(S_2(f)H(f))}{df} \right|_{f=\gamma} > 0$$

The two constraints of the above optimization ensure that the spectrum shapes of the Group I and Group II ETs does not overlap completely. We assign $f_1$ to the left of $f_2$ on the frequency scale (see Figure 5.2(b)). At the point of the intersection of the PSD curves $S_1(f)$ and $S_2(f)$, which we call the cross-over point $\gamma$, the slope of the curves must be positive and negative, respectively. This is calculated by differentiating the respective PSD plots at $\gamma$, to ensure that one of them increases (positive slope) while the other falls (negative slope).

A problem is said to have an optimal substructure if an optimal solution can be constructed efficiently from optimal solutions to its sub-problems. We claim that our proposed optimization also exhibits the optimal substructure property. The proof is included in the Appendix.

With the resulting dual-frequency wireless energy transfer, both groups of ETs can be simul-
taneously active. The final part of this stage involves letting the ETs know that they are cleared for energy transmission through an Acknowledgement (ACK) packet. This packet provides the ETs the center point for the frequencies $f_1$ and $f_2$, according to the optimization results. The ETs know which group they belong to internally, based on the RSS-based band structure shown in Figure 5.3(a). Additionally, the ACK carries an estimated charging time $T$ based on a target voltage level of the capacitor (calculated in Section 5.2.3). This upper limit on the charging voltage is decided by the node’s relative activity in the neighborhood.

After a short SIFS wait period following the ACK (using shorter slot times, for energy, compared to those used for data communication), the ETs begin their transmission. In case of loss of the RFE due to packet collision or bad channel conditions, the contention windows are re-set to the minimum width, thereby initiating an immediate subsequent retry. The design consideration here is that (i) time is critical when a node has extremely low voltage and (ii) nodes will require energy re-charging opportunities much less that the data communication opportunities. Hence, there will not be frequent collision related losses of the RFE arising from the shorter contention window.

### 5.2.3 Adaptive charging threshold selection

As our energy transfer is in-band, each node needs to decide the charging time duration to prevent extended durations of communications outage, possibly, leading to a reduced level of energy replenishment in a single energy transfer stage. Our proposed method defines this upper charging level based on the level of participation in data communication activity for that node with respect to its neighbors. Each node maintains a moving average of the time spent by itself in transmitting and receiving data packets to the total time the channel is used or sensed as “busy”. We find that this simple estimate captures well the node’s relative importance without explicit exchange of information, such as the number of backlogged packets in the MAC queue [61]. Many nodes, hence, will never charge to their maximum capacity, and thereby, they sacrifice their charging opportunity for the larger good of the network performance. The node’s importance index (IDX) is shown in (5.3), where $Tx$ represents the number of data packets that originate from it and $Rx$ denotes the
number of packets destined for the node. Data transfer activity, overhead by the node, that neither originate nor end at it are expressed through \textit{Channel busy time}. The upper charging voltage level \( V_{\text{threshold}}^{\text{max}} \) can be calculated from (5.6).

\[
IDX = \frac{Tx + Rx}{T_x + Rx + \text{Channel busy time}} \tag{5.5}
\]

\[
V_{\text{threshold}}^{\text{max}} = IDX \times (V_{\text{max}} - V_{\text{min}}) + V_{\text{min}} \tag{5.6}
\]

The charging time \( T \) that the node includes in the ACK is calculated as follows, using the standard definitions of energy stored in the capacitor, (5.6) and the trigger voltage \( V_{\text{threshold}}^{\text{min}} \) below which the RFE is set out by the node.

\[
T = \frac{1}{2} C \left\{ (V_{\text{threshold}}^{\text{max}})^2 - (V_{\text{threshold}}^{\text{min}})^2 \right\} \frac{2 \text{Slot energy}}{E_{\text{RX}}} \tag{5.7}
\]

Here, the received energy during the CFE pulses is obtained from two successive time slots, each of duration \( \text{Slot energy} \).

### 5.2.4 Access priority

This channel access determining feature of RF-MAC manifests in two ways: The first is prioritizing between energy transfer and data communication, and secondly, identifying which nodes within the network should send out the data packets first by winning the channel.

**Energy transfer prioritization**

The residual energy of the requesting node is below a threshold \( V_{\text{threshold}}^{\text{min}} \) at the time of sending out the RFE, and hence, there is high likelihood that it may run out of energy. At this stage, it is important that this energy requesting node has higher priority in channel access. This is ensured by
Figure 5.5: CSMA data exchange with energy harvesting aware

separately defining the DIFS duration for energy and data. Consequently, the specially formulated energy request DIFS duration (DIFS\textsubscript{energy}) is shorter than DIFS for data exchange (DIFS\textsubscript{data}), achieved by assigning a shorter slot time for energy request, while data exchange is provisioned with a longer slot time. Hence, we use the slot time of 10\(\mu\)s for energy request and 20\(\mu\)s for data communication as defined in the 802.11 standard \[17\]. Since DIFS is defined as SIFS + 2Slot time\textsubscript{energy}, we derive 25\(\mu\)s for DIFS\textsubscript{energy} and 50\(\mu\)s for DIFS\textsubscript{data}. With the shorter DIFS duration and slot time, RF-MAC prioritizes the energy request over data exchange. The time calculations for the protocol are given in Table \ref{tab:parameters}.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>slot time</td>
<td>10(\mu)s (energy), 20(\mu)s (data)</td>
</tr>
<tr>
<td>\textit{CW\textsubscript{min}}</td>
<td>32</td>
</tr>
<tr>
<td>\textit{CW\textsubscript{max}}</td>
<td>1024</td>
</tr>
<tr>
<td>DIFS\textsubscript{energy}</td>
<td>SIFS\textsubscript{energy} + 2Slot time\textsubscript{energy} = 25(\mu)s</td>
</tr>
<tr>
<td>DIFS\textsubscript{data}</td>
<td>SIFS\textsubscript{data} + 2Slot time\textsubscript{data} = 50(\mu)s</td>
</tr>
<tr>
<td>SIFS</td>
<td>5(\mu)s (energy), 10(\mu)s (data)</td>
</tr>
</tbody>
</table>

Table 5.1: Parameters used in RF-MAC

Data transfer prioritization

In the data exchange phase, the sensor contends for channel using the CSMA/CA mechanism defined in 802.11 \[17\], i.e., it senses the channel for DIFS duration before attempting a transmission. Consequently, sensors with higher energy harvesting rate, owing to their position or conducive
channel characteristics between the ETs and themselves, will have shorter charging durations. They will be able to participate timely for data communication, without interruptions and packet drops for frequent replenishment of energy, all of which contribute to energy usage. We rely on the method proposed in [62], where sensors with higher residual energy get higher priority to transmit. This work proves analytically that this method results in an asymptotically optimal network lifetime. We design RF-MAC in such a way that the sensor’s backoff duration is influenced by its residual energy, i.e., the node with higher residual energy experiences a shorter backoff duration than the node with lower residual energy. An example of the adaptive backoff mechanism for data exchange is described in (5.8). The contention window for data exchange ($CW_{data}$) is randomly selected from the range between the minimum $CW$ and node’s current $CW$, $[CW_{\text{min}}, CW_{\text{current}}]$. We set the contention window of 32 for $CW_{\text{min}}$ in this work. Further, (5.8) shows how the effective slot time is a scaled value based on the residual energy. The capacitor voltage is used for scaling, where it is limited at the higher end by the rated voltage of the capacitor $V_{\text{max}}$ (note this is different from the upper charging threshold in (5.6), current voltage $V_{\text{current}}$, and the $V_{\text{threshold}}$ that signals a critical point if the sensor needs to be kept in operation.

\[
\text{Backoff} = DIFS_{\text{data}} + CW_{\text{data}} \times \{\text{Slot}_{\text{energy}} + \frac{(V_{\text{max}} - V_{\text{current}})(\text{Slot}_{\text{data}} - \text{Slot}_{\text{energy}})}{V_{\text{max}} - V_{\text{threshold}}_{\text{min}}}\} \]

The overall process of data exchange is explained using Figure 5.5. Sensors $S_1$, $S_2$, and $S_4$ all have packets to transmit to sensor $S_3$ at the start (indicated by the arrow on the time axis). They each sense the channel for $DIFS_{\text{data}}$. Intuitively from (5.8), sensor $S_2$ with residual energy of 3.0 v, should experience the shortest backoff duration, as opposed to $S_1$ and $S_4$. However, this does not imply that the nodes with higher residual energy will always have shorter backoff duration, as the random selection of the backoff slots within the window does contribute to the overall backoff time. This selection from the window $[CW_{\text{min}}, CW_{\text{current}}]$ is independent of node’s residual energy.
5.3 Simulation Results

In this section, we thoroughly evaluate our proposed MAC protocol using the ns-2 simulator. We observe the behavior of RF-MAC protocol with respect to the following metrics: (i) number of energy transmitters, (ii) number of data flows, (iii) numbers of nodes, and (iv) packet size. The simulation parameters are set as follows: The EH circuit parameters are from [14]. We model the ETs on the Powercaster transmitter [15], which radiates continuous waves at 3 W. The operational characteristics of the sensor, such as energy spent in transmission, reception, idle listening, channel bandwidth, etc. are from MICA2 specifications [4]. Additional parameters used in the simulation are present in Table 5.1. Unless specifically stated, 300 sensor nodes and 256 ETs are deployed uniformly at random in 50 x 50 m^2 grid. The default packet size is 50 Bytes and the sender/receiver pairs are chosen randomly from the set based on the random number generator in ns-2.

We compare three different protocols: 1) RF-MAC-opt, 2) RF-MAC-no-opt, and 3) Unslotted CSMA. RF-MAC-opt is the full-featured RF-MAC, including the frequency optimization and ET selection, adaptive charging threshold, and channel access priority mechanisms, as discussed in Section 5.2. The RF-MAC without the optimization (named RF-MAC-no-opt) has the above features other than assigning different frequencies to the two groups of ETs, i.e., it makes no attempt to identify and classify ETs based on their phase mismatch. Finally, the unslotted CSMA modified from the description in [39] provides the base case and reference protocol for comparison. Here, each sensor node may issue the RFEs and receive the CFEs. However, there is no attempt made to calculate the optimal charging time, and it has none of the mentioned features of the RF-MAC protocol. Once an RFE is sent out, the node charges to its maximum capacity, which does not take into consideration the impact on data traffic.

5.3.1 Impact of the number of ETs

In this sub-section, we investigate the effect of the number of ETs on the average harvested energy and average network throughput for different MAC protocols. Figure 5.6 shows the effect of the
ET density on the average harvested energy of two RF-MAC variants. The ET density, defined as the average number of ETs located within node’s radio range, is varied from 1 to 12. It is clear that RF-MAC-opt delivers monotonically increasing average harvested energy with increasing the number of ET density. RF-MAC-no-opt, on the other hand, experiences fluctuation throughout the study range. The benefit of the frequency optimization greatly improves the performance as it maximizes the energy transfer by separating the two transmission spectrum and ensuring the highest level of energy delivery. Without this optimization, ETs enter the charging process and do not take into account the possibility of destructive interference, resulting in sub-optimal energy transfer.

![Figure 5.6: Effect of the number of ETs on average harvested energy](image)

The average network throughput is shown in Figure 5.7 and the pattern resembles to that of the average harvested energy plot. Both variants of RF-MAC yield higher average network throughput as ET density increases. However, it is obvious that the average network throughput of RF-MAC-opt is significantly higher that RF-MAC-no-opt, about 62% increase on average. Both the average harvested energy and average network throughput of unslotted CSMA is the lowest of all protocols. This is because the unslotted CSMA does not have features offered by the RF-MAC protocol. In
Figure 5.7: Effect of the number of ETs on average network throughput

In this case, RF-MAC-opt yields over 100% and 300% more than the unslotted CSMA in terms of the average harvested energy and average network throughput, respectively. It can be inferred from Figures 5.6 and 5.7 that as the ET density increases, the more RF-MAC-opt outperforms the other schemes.

Figure 5.8: Effect of multiple flows on average harvested energy
5.3.2 Impact of multiple flows

The effect of multiple simultaneous flows in the network was investigated, with random selection of source and destination nodes while the number of flows are varied from 1 to 6. Again, we observe the behavior of RF-MAC on two metrics, the average amount of harvested energy and average network throughput, when nodes experience different levels of channel usage and traffic load. Figure 5.8 shows a smooth and monotonic increase in the average harvested energy of RF-MAC-opt as the number of flows increases. Even though the RF-MAC-no-opt exhibits a similar pattern, the increase is not as smooth as one with the frequency optimization. Evidently, the amount of average harvested energy yield could be almost 200% less than RF-MAC-opt. Figure 5.9 depicts the average network throughput of RF-MAC with various numbers of data flows. Interestingly, the average network throughput of both RF-MAC variants gracefully drops as the number of data flows increases. This reduction in average network throughput is a result of more nodes sending out RFEs as they deplete their energy faster with increasing number of data flows. Consequently, the network spends more time in the charging state and hence less time spent in the data exchange state. However, RF-MAC-opt yields higher average network throughput, approximately 20% more.
in this case. Again, both variants of RF-MAC largely outperform the unslotted CSMA. Especially, RF-MAC-opt yields approximately 112% increase in terms of average network throughput.
5.3.3 Impact of the number of sensor nodes

We investigate how RF-MAC protocol behaves when the number of sensor nodes in the topology changes. We randomly deploy various numbers of sensor nodes in the topology, ranging from 60 to 240. The average harvested energy is shown in Figure 5.10, wherein the performance of RF-MAC-opt smoothly drops and tends to stabilize when 120 sensor nodes or more are present. On the other hand, RF-MAC-no-opt yields a similar pattern to the unslotted CSMA, a rather constant average harvested energy with fluctuation around the mean trend. Again, RF-MAC-opt offers higher average harvested energy throughout when compared to RF-MAC-no-opt. Figure 5.11 depicts the average network throughput of RF-MAC with different numbers of sensor nodes. Similar to the earlier case with the average harvested energy, both RF-MAC variants experience the reduction in average network throughput even RF-MAC-opt displays marginally higher throughput. Moreover, the unslotted CSMA performs significantly lower than RF-MAC-opt and RF-MAC-no-opt in both average harvested energy and average network throughput.

![Figure 5.12: Effect of the packet size on average harvested energy](image)

Figure 5.12: Effect of the packet size on average harvested energy
5.3.4 Impact of packet size

The packet size is varied from 30 to 90 bytes with an increment of 20 bytes, while other parameters are kept to their default settings. The impact of packet size on the average harvested energy of RF-MAC is shown in Figure 5.12. It is clear that the average harvested energy of RF-MAC-opt is monotonically increasing, with an increasing packet size, and offers up to 25% gain over RF-MAC-no-opt at the packet size of 90 bytes. On the other hand, the average harvested energy of RF-MAC-no-opt tends to stabilize for packet sizes larger than 50 bytes. The average network throughput of RF-MAC is shown in Figure 5.13. Both RF-MAC variants offer an increase in average network throughput with increasing packet size. Again, the RF-MAC-opt outperforms, in terms of the average network throughput, its non-optimized variant and the unslotted CSMA throughout the study range.

5.4 Section Summary

The RF-MAC protocol defines new metrics and methods for selection of RF energy transmitters or ETs, that ensures high lifetime of the sensor nodes. The grouping of the ETs into two sets with
varying transmission frequencies, and the minimal control overhead are both geared to keep the hardware requirements simple, and the protocol easy to implement. Our protocol delves on the important issue of how to determine the energy vs. data communication tradeoff, especially as one occurs as the cost of the other. Finally, simulation results reveal that RF-MAC largely outperforms the unslotted CSMA in both average harvested energy and average network throughput. The features incorporated in RF-MAC efficiently optimize the energy delivery while minimizing the data exchange disruption. Our future effort will focus on deriving an analytical model of this protocol and complete demonstration on off-the-shelf sensor motes.
Chapter 6

Impact of Mobile Transmitter Sources on RF Energy Harvesting

Wireless energy harvesting sensor networks constitute a new paradigm, where the motes deployed in the field are no longer constrained by the limited battery resource, but are able to re-charge themselves through directed electromagnetic energy transfer. The energy sources, whom we call actors, are mobile and move along pre-decided patterns while radiating an appropriate level of energy, sufficient enough to charge the sensors at an acceptable rate. First, we propose two event-specific mobility models, where the events occur at the centers of a Voronoi tessellation, and the actors move along either (i) the edges of the Voronoi cells, or (ii) directly from one event center to another. We then undertake a comprehensive simulation based study using traces obtained from our experimental energy harvesting circuits powering Mica2 motes.

6.1 Energy transferring through Mobile Actors

Our proposed method of energy transferring relies on actors that move along a region that is partitioned into Voronoi cells. First, we describe how these cells and paths are constructed.

Let \( S = \{p_1, p_2, ..., p_i, ..., p_n\} \) the set of the points that correspond to specific event locations in the region of interest. These event locations typically signal a feature of interest, such as an
extreme temperature, that requires continuous sensing and transmission for the sensors close to
that point. Let $V(p_i)$ denote the set of all sensors that are closer to the event point $p_i$, than any
other point belonging to $S$.

$$V(p_i) = \{ x : |p_i - x| < |p_j - x|, \forall j \neq i \}$$  \hspace{1cm} (6.1)

Next, we describe the two mobility models that we shall use in this investigation.

### 6.1.1 Mobility Models for the Actors

In the first mobility model, called center-to-center mobility model (CM), the actors move along
paths that connect the EPs. We use the traveling salesman problem algorithm to construct the
connected paths from one event point to the next, so all the points are eventually traversed (see
Figure 6.1(a)). Here, the focus is to ensure that the sensors close to the Voronoi cell centers,
i.e., the respective EPs of the Voronoi cells, have the maximum possible lifetime. However, this
“event-centric” energy transfer may not be representative of a wider class of WSN applications,
where multiple nodes forward data packets towards a sink. Thus, not only nodes close to the EP,
but also in the peripheral region need to be actively charged.

In the second mobility model, called as around edges moving model (EM), the actors move
along the edges of the Voronoi cells. The key aspect of using the edge is that the energy transfer
occurs on a much wider extent, covering those nodes that may potentially be farther away from the
event point. However, such nodes may well participate in data forwarding, and need to be charged
as long as as the sensors close to the event generate readings. Assuming that actors are initially
assigned to individual vertices of the Voronoi cells, they continue to move back and forth along all
edges that intersect that vertex. In Figure 6.2(a) the motion is showed by the bold dark line, for
the rightmost vertex of the tessellation.
6.1.2 Initial Deployment of the Actors

While the mobility model is mainly responsible for assured transfer of energy, the initial deployment has significant bearing on the efficiency of this transfer. If there is a mass concentration of actors in any one location, then the other areas of the network get starved of future energy transfers. Hence, we delve into the deployment issue in detail.

First, we present a case for the deployment of actors for the CM model. The steps are as follows:

- **Step 1:** If the number of actors is greater than the number of EPs, first, one actor is deployed in each EP in turn.

- **Step 2:** Repeat Step 1 until the remaining actors are less than the EPs (see Figure 6.1(a) that shows an example of 4 EPs and 11 actors).

- **Step 3:** Once all the actors are deployed in the EPs they are re-positioned equidistantly from each other on the edge connecting two successive EPs belonging to the traversal path (see Figure 6.1(b)).

Thus, we get a final distribution of actors with the maximum coverage along the traversal edges.

For the actor deployment in the EM model, we outline the following steps.

- **Step 1:** If the number of actors is greater than the number of inner Voronoi corners, first, one actor is deployed in each corner.
• **Step2**: Repeat **Step1** until the remaining actors are less than the inner corners (see Figure 6.2(a) that shows an example of 4 EPs and 11 actors).

• **Step3**: Once all the actors are deployed in the corners they are redistributed in the different branches following the same method, such as each branch has the same number of actors (or close).

• **Step4**: Finally, each actor belonging to a given branch is re-positioned equidistantly from each other connecting the two successive inner corners (see Figure 6.2(b)).

![Figures 6.2(a) and 6.2(b)](image)

(a) Starting distribution among edges  
(b) Final equidistant distribution

**Figure 6.2**: Actor deployment for EM

### 6.1.3 Moving actors and energy propagation

We let the actors move with constant speed along the chosen paths. Irrespective of the mobility model used, the actors radiate just enough energy to charge the sensors close to the events, i.e., around the EPs, considering a minimum required power at the EP. Also, the energy consumed by an actor for its physical movement at a speed of 2 m/s is 150 mW, given by [51]:

\[
E_v(W) = 0.05 \frac{W}{m/s} \gamma, \quad \gamma = 1.5
\]

(6.2)

To compute the required energy to be transmitted by an actor to provide the energy level requested around the EP, the Friis equation [3.1] is used. \( R \) is the emitter-receiver distance. This
The equation is a function of the frequency (here, expressed through the wavelength $\lambda$) as it varies from $f = 642 \text{ MHz}$ ($\lambda = 46.7 \text{ cm}$) to $f = 915 \text{ MHz}$ ($\lambda = 32.8 \text{ cm}$). Consequently, the required energy increases proportional to the square of the frequency variation. Due to the limitation of the harvesting circuits, any power received under $-20 \text{ dBm}$ has been considered null. Friis equation, altogether with unitary antenna gains and isotropic antenna propagation are used here to simplify the simulation. Also multipath effect is neglected for tractability of the simulation.

### 6.2 Performance Evaluation and Observations

#### 6.2.1 Simulation Setup

We use MATLAB to study the impact of mobility in this work, with all the parameters chosen for MICA2 motes and our harvesting platform characteristics [14]. We use the stop condition for the simulation as follows: When the sensor coverage reduces to 50% of the area of deployment, with 5 m sensing radius of each node (i.e., as nodes start dying owing to energy loss), the simulation for that run is stopped. All calculations of residual energy mentioned in this section are obtained from the average values of the sensors closest to their respective EP. The power consumed by actors is calculated as the average over the cycles (time slots) of the sum of all the actors’ individual consumption. Table 6.1 shows the default parameters used in this thesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of consuming</td>
<td>1/30</td>
<td>1/[10,20,30,40]</td>
</tr>
<tr>
<td>Max TX power</td>
<td>36</td>
<td>36 dBm</td>
</tr>
<tr>
<td>No. of actors</td>
<td>10</td>
<td>10,20,30,40</td>
</tr>
<tr>
<td>No. of Event Points</td>
<td>10</td>
<td>10,20,30,40</td>
</tr>
<tr>
<td>Min required power at EP</td>
<td>-5</td>
<td>-20,-10,0,5,10 dBm</td>
</tr>
<tr>
<td>Harvesting Frequency</td>
<td>915</td>
<td>642MHz,915MHz,2.4GHz,5.1GHz</td>
</tr>
<tr>
<td>Area</td>
<td>200</td>
<td>150,200,250 $m^2$</td>
</tr>
</tbody>
</table>

Table 6.1: Parameters for the simulations
6.2.2 Observations

As we evaluate each parameter, we vary it for four different types of mobility models (shown on the X-axis), i.e., (i) static actors placed along the edges in the EM case (called as static-EM), (ii) mobile actors for the EM case (called as mobile-EM), (iii) static actors placed on the EPs, for the CM case (called as static-CM), and (iv) mobile actors moving from one EP to another, again for the CM case (called as mobile-CM). We evaluate the impact of mobility with respect to the following parameters:

Minimum received power at EP

![Graph showing total consumed energy per cycle for different mobility models and power requirements](image)

Figure 6.3: Total actors consumed energy/cycle

Figure 6.3 shows the energy consumption of actors with various values of the minimum required power at the EP. It is clear that both the cases of static and mobile EM show little deviation with the change in this power requirements at the EP. In the EM case, the actors are rarely close to the EP, and thus the actors are always forced to transmit at a higher power than the minimum required level. On the other hand, for the CM case, actors pass really close (over the point), and hence, at some instances, the transmission power can be drastically reduced, producing a bigger variation.
Figure 6.4 shows the residual energy of sensors. Overall, mobile scenarios indicate an increase of residual energy while it is almost constant in static models. Also, there is considerable increment in residual energy in mobile CM compared to mobile EM. This is because, in mobile CM, sensors get a higher recharging rate when the actors are close to the EP and transmitting at a high power.

![Figure 6.4: Average sensors residual energy](image)

**Frequency of energy transmission for the actors**

The effect of transmission frequency on the energy consumption of actors and the residual energy of sensors are shown in Figures 6.5 and 6.6, respectively. In Figure 6.5, it is clear that the influence on the increment of energy consumed by the actors is not substantial (3% increment from 642 MHz to 915 MHz). On the contrary, the improvement over the residual energy level on sensors is drastic (50% increment from 915 MHz to 642 MHz mobile EM). This deviation is larger in CM as the actors pass very close to the sensors used for residual energy calculations. On the other hand, in EM, all the sensors located around the middle regions of the Voronoi cell get a good average charging rate, as shown in Figure 6.6.

Figures 6.7 and 6.8 show the energy consumption of actors and the residual energy of sensors of mobile EM, respectively, with both transmission frequency and minimum required power at the
EP. With low minimum required power requested (at $-20\,\text{dBm}$), there exists a large variation in energy consumption of actors while the residual energy of sensors tends to be somewhat constant. The constant level of the residual energy is because all the received energy is more influenced by actors’ power level than the path loss. The large variation in consumed energy is due to different level of effort undertaken by the actors to allow the sensors around the EP to receive the required power. The difference in consumed power is approximately 3 times, from 642 MHz to 5.1 GHz.
With higher minimum required power (at 20 dBm), the residual energy of sensors shows a large variation, while the consumed energy asymptotically converges for the actors. The large variation in residual energy is a result of the pathloss effect. The constisence in consumed energy is because actors are forced to transmit with the highest power allowed, omitting the required power by the EP.

![Figure 6.7: Average sensors residual energy when the minimum required power at the EP varies](image)

Figure 6.7: Average sensors residual energy when the minimum required power at the EP varies

![Figure 6.8: Average sensors residual energy when the minimum required power at the EP varies](image)

Figure 6.8: Average sensors residual energy when the minimum required power at the EP varies
Figures 6.9 and 6.10 show the consumed energy of actors and residual energy of the sensors. At first glance, the increase in the number of actors seems to give a linear increment on the residual energy, and there exists a strong dependency within a moving model. In the CM case, as the actors move in the same direction at all time, this expected result is intuitive. However, in EM, actors go back and forth from their original position to the neighboring Voronoi corners. Consequently, increasing number of actors does not guarantee an increase in both consumed and residual energy. It is also clear that the increase in energy consumed in CM is larger, while the variation in EM tends to be smaller.

**Number of event points**

As we vary the number of event points, i.e., the EPs, the number of corresponding Voronoi cells also changes. Thus, as EPs increase, on one hand the overall length of edges that the actors need to travel increases, while on the other hand the inter-event distance decreases. Thus, the actors spend reduced amount of transmission energy for re-charging sensors around the EP (though mobility-caused energy consumption by the actors is higher). Additionally, as the actors move along the
edges back and forth that intersect the initial deployment vertex, on average, higher amount of actors are needed for the network. These observations are evident in Figure 6.11 where we see how the energy consumption is impacted, when we vary the number of EPs with 10 actors.
Probability of sensor energy consumption

This parameter, whose purpose is to evaluate how the sensor sleep-awake cycle influences the network, is the inverse of average sleeping time of the sensors (displayed in Table 6.1). The energy spent by the actors is kept constant, independent of the probability of energy consumed by sensors. Figure 6.12 indicates how the residual energy of sensors increases significantly, and the significant variation suggests it is a good parameter to be tuned in order to increase the network lifetime.

Area scenario

We initially performed the simulation varying the measurement area with a fixed number of sensors. This resulted in an abrupt energy depletion of some sensors due to sparse sensor density, and thus, terminating the simulation prematurely. Thus, we determined it was crucial to maintain a constant sensor density so that the simulation delivers comparable results. Figures 6.13 and 6.14 show the consumed energy of actors and residual energy of sensors, respectively, with various area sizes. While the increment of the consumed energy of actors is negligible, the residual energy of sensors tends to increase up to 4 times as the deployment area is varied from 250 $m^2$ to 150 $m^2$ for...
mobile CM, and up to 3 times for mobile EM for the same conditions.

### 6.2.3 Network lifetime

We next investigate the improvement in network lifetime (all results are in the unit of seconds) with respect to various parameters as mentioned below:
• Frequency variation: Figure 6.15 shows the effect of various transmission frequencies on the network lifetime. Following the pathloss equation, the lower frequencies are less susceptible to signal attenuation. This directly results in stronger received signal, and hence, prolonged network lifetime.

• Increasing of number of actors: Figure 6.16 shows the effect of number of actors on network lifetime. It is clear that increasing number of actors increases the network lifetime. Moreover, the mobile movement model delivers a smoother improvement than the static movement model.

• Number of event points: Figure 6.17 shows the effect of number of event points on network lifetime. Non intuitively, increasing number of event points yields an improvement in terms of energy consumption, but there is a negligible improvement in network lifetime with this increase. The reason is as follows: The energy transmitted by the mobile nodes is utilized more efficiently with more sensors requiring energy (the total time for energy transmission remains same in all cases). However, the extra load of charging these multiple event points increases the traversal time of the mobile actors, and overall, there is no improvement in the
lifetime.

Figure 6.16: Number of actors

Figure 6.17: Number of event points (EPs)
6.3 Section Summary

From our investigation of the various mobility models, there are certain scenarios that are particularly suited for either the CM or the EM, which we summarize below:

- The sensors have a certain minimum incident power requirement for charging the storage capacitor. This threshold power level does not significantly impact the EM case. However, judicious selection of this level becomes very important for the CM case, which impacts the storage energy drastically (e.g., in CM for a variation of 5 dBm in the minimum required power for re-charging, the percentage increase in the storage energy is over 85% for the entire network).

- The lower frequency bands have a significant improvement in the network lifetime. Importantly, there is a large difference (e.g., 50% when using the EM case) in the residual energy levels for the sensors with the use of lower frequencies (when using channels in the 600 MHz band, over 900 MHz).

- The increase in the number of energy transferring actors has a direct influence in the CM case, while for EM, it depends predominantly on the geometry of the scenario. This is because the path traversal length for typical deployment scenarios often outweighs the gain from multiple active actors.

- The duration of the awake time for the sensors impacts the network lifetime to a large extent in the case of CM. For e.g., a variation from 20 to 30 seconds gives an increase of 35% in the residual energy level, and 30% improvement in the lifetime, while maintaining a constant energy consumption ratio.

We conclude with the general assessment that the CM gives better performance in small deployment scenarios, and when there is a higher density of sensors concentrated around the event points. The EM provides better results on large deployment scenarios where the sensor density is lower and the events are scattered, with higher separation distance between them.
Chapter 7

Conclusion

We show that with a simple yet optimal design and optimization, the prototype can yield almost double the efficiency than that of a major commercially available energy harvesting circuit in the low incident power range (simulation results for the circuit reveal about 70% operational efficiency). Our study implies that Mica2 sensor motes can be perpetually operated when their duty-cycle is carefully selected based on the incident RF power (as low as $-6\, \text{dBm}$). Moreover, the prototype is able to sustain the energy neutral of Texas Instruments’ MSP430G2553 in LPM4 at $-20\, \text{dBm}$. The experimental results are in good agreement with the values seen in the non-ideal simulation. We also compare our prototype’s efficiency with the commercially available RF energy harvester from Powercast, where our prototype largely outperforms the Powercast P1100 in the range of $-20\, \text{dBm}$ to $7\, \text{dBm}$. Finally, in order to have a performance improved and lower cost, the circuit needs to be implemented as “System on Chip” as it suffers less above mentioned parasitics, and we will pursue this in our future work.

We proposed two cross-layered protocols for Energy Harvesting Networks, Device-Agnostic (DA) and Device-Specific (DS). A thorough performance evaluation was conducted with various important metrics, including duty cycles, number of energy transmitters, network load and multiple flows. The duty cycle of DS scheme is much higher than that of DA scheme. In most applications where throughput is of most concern, the DS scheme is preferable over DA and VA
scheme due to higher throughput yielded. The DS scheme also yields marginally higher latency than the VA scheme. However, the significantly higher throughput of the DA scheme can easily offset the marginal latency incurred. On the other hand, the lower latency of VA scheme makes it suitable for applications which the lowest latency is required. The lowest latency requirement becomes insignificant as the network converges to the saturation point, i.e. the data rate of the radio employed.

The RF-MAC protocol defines new metrics and methods for selection of RF energy transmitters or ETs, that ensures high lifetime of the sensor nodes. The grouping of the ETs into two sets with varying transmission frequencies, and the minimal control overhead are both geared to keep the hardware requirements simple, and the protocol easy to implement. Our protocol delves on the important issue of how to determine the energy vs. data communication tradeoff, especially as one occurs as the cost of the other. Finally, simulation results reveal that RF-MAC largely outperforms the unslotted CSMA in both average harvested energy and average network throughput. The features incorporated in RF-MAC efficiently optimize the energy delivery while minimizing the data exchange disruption. Our future effort will focus on deriving an analytical model of this protocol and complete demonstration on off-the-shelf sensor motes.

The study on the impact of mobile energy transmitters focuses on the scenario that the energy sources, whom we call actors, are mobile and move along pre-decided patterns while radiating an appropriate level of energy, sufficient enough to charge the sensors at an acceptable rate. This is the first work that investigates the impact of energy transfer, especially concerning the energy gain in the sensors, the energy spent by the actors, and the overall lifetime in the resulting mobile sensor-actor networks. We propose two event-specific mobility models, where the events occur at the centers of a Voronoi tessellation, and the actors move along either (i) the edges of the Voronoi cells, or (ii) directly from one event center to another. Our results provide guidelines on which mobility model may be adopted based on the distribution of the events and actors.
Appendix

Proof of optimality of energy transfer

Statement: Given the power spectral density $S_1(f)$ and $S_2(f)$, the total energy transfer ($E_{RX}^{Max}$) under the RF energy harvesting circuit’s frequency response $H(f)$ is maximum.

\[
E_{RX}^{Max} = \int_{f_1-\varepsilon}^{f_1+\varepsilon} S_1(f)H(f)df + \int_{f_2-\varepsilon}^{f_2+\varepsilon} S_2(f)H(f)df \\
- \{ \int_{f_2-\varepsilon}^{\gamma} S_2(f)H(f)df + \int_{\gamma}^{f_1+\varepsilon} S_1(f)H(f)df \}
\]

is maximum then

\[
\int_{f_1-\varepsilon}^{f_1+\varepsilon} S_1(f)H(f)df - \int_{f_2-\varepsilon}^{\gamma} S_2(f)H(f)df \text{ and}
\]

\[
+ \int_{f_2-\varepsilon}^{f_2+\varepsilon} S_2(f)H(f)df - \int_{\gamma}^{f_1+\varepsilon} S_1(f)H(f)df
\]

are maximum as well

Proof: Let $(1) - (3)$ give the area under the curve represented by $X$ and $(2) - (4)$, similarly, return the area of $Y$, then $(1) + (2) - \{(3) + (4)\}$ has the total area of $X+Y$. Assume we find $\alpha$ such that $\alpha = (1) - (3) + \epsilon ; \epsilon > 0$ then the total area $= (1) + (2) - \{(3) + (4)\} + \epsilon = X + Y + \epsilon > X + Y$. This contradicts the supposition that $(1) + (2) - \{(3) + (4)\}$ is maximum. $(1) - (4)$ can be proved in a similar fashion.
Bibliography


