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Design optimization and implementation for RF energy harvesting circuits

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Design Optimization and Implementation for
RF Energy Harvesting Circuits

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Abstract

The objective of this research is to propose a novel circuit design that enables wireless energy harvesting, which is a new paradigm that scavenges energy from radio frequency (RF) electromagnetic radiation. Compared to other commonly observed alternative energy sources, such as solar and wind, RF harvesting can provide continuous supply of energy, and is not completely impaired by bad weather conditions and indoor use. However, obtaining a usable yield from this energy source is challenging as the amplitude of the arriving signals is considerably low, and the requirements for operating a commercially available sensor mote are proportionally high. The existing state-of-the-art solutions are effective only over narrow frequency ranges, are limited in efficiency response, and require higher levels of input power for successful operation. Thus, this research aims to further the state of the art through the design and optimization of a novel RF harvesting board design and exploring the interfacing challenges of this board with a number of practical wireless sensors.

The contribution of this thesis goes beyond conceptual design alone, and has fabrication 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. Results reveal approximately 100 % improvement over other existing commercialized designs in the power range of $-20$ to $-7$dBm for the Mica2 mote, and a considerable increase in the wake-up range when a modification of our circuit is used together with a RFID powered WISP mote.
Acknowledgements

I would like to thank my adviser, Dr. Kaushik R. Chowdhury, for his great help, support and guidance given throughout the thesis period.

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Chapter 1

Introduction

Energy is a basic necessity for sustaining human life, which pervades each and every one of our activities. In the very early days, we used muscle power (both human and animals) to drive simple implements and machines, which could only run for a limited time and had limitations on their continuous availability. The biggest transition happened when we learnt to generate energy, by transforming one state of energy, possibly latent, to another. Suddenly, vast possibilities opened up where energy could be obtained, stored, and transferred across large distances.

As an essential keystone in furthering the reach of technology and a catalyst for economic development, it is becoming hard to meet the insatiable need of energy today. According to IEA total world energy supply was 102,569 TWh (1990); 117,687 TWh (2000); 133,602 TWh (2005) and 143,851 TWh (2008). World power generation was 11,821 TWh (1990);
The increasing energy demand puts a strain on current energy sources. Fossil fuels, which comprise a majority of current output, are being depleted. Other classical sources, such as coal, may result in adverse environmental effects. As a very recent occurrence, the devastating destruction of the nuclear plant in Fukushima in Japan has brought about a review and closure of many similar grade energy generation facilities worldwide. Thus, there is an incessant effort to identify new sources of energy that may partially satisfy the energy demands and conserve our finite natural resources for the years to come.

Renewable energy sources provide an alternative to conventional natural sources, of which there are limited supplies. Renewable energy can be broadly defined as a kind of energy that is generated from natural sources, which is not typically depleted, such as sunlight, wind, rain, tidal motion, flowing water, biomass, geothermal heat, among others. According to the International Energy Agency, renewable energy is derived from natural processes that are replenished constantly. Some additional features of renewable energy sources that make them an attractive alternative to the classical natural sources are:

- Renewable energy sources are often accessible without geographical and national barriers, though certain regions may be more conducive to their large-scale use (e.g., coastal regions for tidal energy; countries situated around the equator for solar energy).

- Renewable energy sources generally do not result in harmful by-products of generation, which adversely affect the environment. Hence, they are very clean and safe to use.

- These sources are inexhaustible in the near term, unlike fossil fuels, which are getting used up faster everyday. They are generally free to harness, though specialized equipment may be needed for high conversion efficiency.

Figure 1.2: Energy harvesting systems, courtesy of [12]
A complete overview of the how energy from different sources is generated, stored and consumed is given in Figure 1.2. The technique of converting this raw energy source into useful electrical energy is called as energy harvesting. Quoting the Energy Harvesting Forum, energy harvesting is the process of capturing minute amounts of energy from one or more of these naturally-occurring (renewable) energy sources, accumulating them and storing them for later use [9]. A similar viewpoint is reflected by the industrial sector. According to Dr. Peter Harrop, the Founder and Chairman of IDTechEx, a large company studying on energy harvesting and storage, energy harvesting is the conversion of ambient energy into electricity to drive small or mobile electronic and electrical devices [10]. It is interesting to note that not all renewable source of energy have equivocal support. Wind power, such as the large scale deployment in the Cape Cod region in Massachusetts, US, continues to draw the ire of environmental groups that argue about its detrimental impact on coastal populations [11].

Typically, in commercial energy harvesting systems, the energy harvested from renewable resources firstly arrives at boost converters that scale up the voltage, followed by battery management systems where this energy is stored. In this way, it is converted into a useful and regulated form for many small electronic and mobile applications, such as a wireless sensor network, depicted in Figure 1.3.

![Energy harvesting systems diagram](image)

Figure 1.3: Energy harvesting systems diagram

As energy harvesting becomes technologically viable, one might wonder what advantages it has over traditional methods of energy generation and storage. Four advantages of energy
harvesting that provide useful clues in this context are [9]:

- The efficiency of the energy harvesting devices has increased with recent technical developments, especially while capturing energy from ambient sources. Additionally, power consumption of engineered devices is reducing over time, with advancements in microprocessor technology. In combination of the above two facts, energy harvesting is becoming a viable way to drive many low-power applications, potentially replacing current sources of power in the future.

- Energy harvesting can be a maintenance-free alternative to battery technology, which is costly and inconvenient to replace. Thus, lifetime of the appliance may be unlimited if run with well-designed energy harvesting systems. If the source of the energy is guaranteed to available, energy harvesting systems can be used more reliably than battery and plug-based connections.

![Figure 1.4: The improvements in technology comparing batteries with other devices.](image)

- Energy harvesting can be used as backup generator in power systems, which helps to improve the reliability and prevent power interruptions.

- Energy harvesting systems can provide mobility to devices, which are dependent on the traditional plug-based electricity sources. Thus, some wired (cable-driven) applications...
are transformed into wireless applications.

Energy harvesting systems can be classified according to the source which energy is harvested from. The most commonly observed energy harvesting systems are based on the following:

- Mechanical Energy (piezoelectric vibrations, human body movement, etc.)
- Thermal Energy (using geo-thermal energy of the earth, difference in temperatures of two points of a conductor etc.)
- Light Energy (primarily, solar energy)
- Electromagnetic Energy (mainly from radio frequency waves, magnetic coupling)

![Diagram of RF energy harvesting systems](image)

Figure 1.5: The principle of RF energy harvesting systems.

Of the above types of energy harvesting systems, the scope of our research is limited to Radio frequency (RF) energy harvesting. We therefore explore this topic in detail in the following sections.

### 1.0.1 Radio Frequency Based Energy Harvesting

This technique of energy harvesting relies on the energy contained in the RF fields generated by electromagnetic wave transmitters, such as TV towers, wireless radio networks and cell phone towers. Conceptually, this energy is captured and converted into functional DC voltage by using a specialized circuit directly connected to a receiving antenna.

Although this technique has least energy intensity compared to other energy harvesting systems, RF energy harvesting systems have many useful features, not present otherwise.
Such systems can be used in any location that has a high incidence of strong ambient RF waves, or in specific applications where there is a presence of a dedicated transmitter. Hence RF energy harvester is generally not dependent on time of the day, geographical aspects of the region, weather conditions etc., which must be considered in other examples of energy harvesting systems including solar, and wind energy. RF energy can also be used to drive more than one device at the same time. For instance, the energy spread from any omnidirectional transmitter (TV tower, GSM base station etc.) can be scavenged by more than one RF energy harvester. Figures 1.5 and 1.6 demonstrate the principle and architecture of RF energy harvesting systems.

Figure 1.6: RF energy harvesting system architecture

1.0.2 Application Areas of RF Energy Harvesting

With the growing popularity and applications of large-scale, sensor-based wireless networks (e.g., structural health monitoring, human health monitoring, to name a couple), the need to adopt inexpensive, green communications strategies is 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 [17]. This can potentially lead 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.

The concept of wireless energy harvesting and transfer is not new; rather it was demonstrated over 100 years ago by Tesla [4]. In recent times, RFID technology is a clear example of wireless power transmission where such a tag operates using the incident RF power emitted by the transmitter [5]. 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 micro controller on the MICA2 mote [2]. 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 W), there is a visible need for revisiting energy harvesting circuit design that can successfully operate a sensor node.

![Diagram of RF Energy Harvesting System]

**Figure 1.7: Ambient RF energy harvesting**

### 1.0.3 Components of RF Energy Harvesting System

Figure 1.7 shows the components of 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 +Vcc 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. This problem is addressed by considering a multi-stage design of the voltage multiplier, whose operating points are decided by solving an optimization framework.

1.0.4 Thesis Contributions

This thesis summarizes the main contributions of the work as follows:

- Our work demonstrates 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.

- This work utilizes 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). An optimization framework is developed to decide the switch-over 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 dBm to 20 dBm.

- Our work achieves the interfacing of proposed circuit with a commonly available Mica2 sensor mote, and then characterizes through experiments, the impact on the duty cycle of such an integrated device that is powered by harvesting alone.

- Our effort explains how to 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 the 915 MHz ISM band is chosen as it allows direct comparison with the commercial solution from Powercast. 

\[1\text{The 915 MHz ISM band is chosen as it allows direct comparison with the commercial solution from Powercast.} \]
terms of efficiency and generated voltage. The non-ideal simulation provides a bound on achievable efficiency with respect to a particular design.

• The use of multiple input antennas is investigated for increasing the amount of energy harvested. The simulation result shows that it is feasible, although there exists a bound on numbers of antennas implemented.

• In addition this work includes another circuit design, composed of same components with PCBs by using same parameters and design strategies, but interfaced with wireless identification and sensing platform (WISP), instead of the Mica2 mote. This greatly improves the wake-up range required by WISP to trigger an interrupt to the Tmote Sky mote.

The rest of this thesis is organized as follows:

• Chapter 2 gives information about the related work,

• Chapter 3 describes the design, simulation results, measurement and fabrication of the dual-stage circuit design. Additionally, it gives information about interfacing the fabricated circuit with MICA2 mote.

• Chapter 4 depicts the design, simulation results, measurement and fabrication of the circuit design for Wake-up Radio study. Additionally it gives results on using the fabricated circuit with existing work wake-up radio, to increase its operational range.

• Chapter 5 presents some conclusions and future work.
Chapter 2

Related Work

Energy harvesting has been in the focus of the research community in recent years. The energy harvesting systems can be classified according to energy sources scavenged from ambient environment as shown in Figure 2.1. Table 2.1 shows the estimated power that can be harvested from different ambient sources. In this section, various types of energy harvesting research from both academic and industrial sectors are presented.

![Figure 2.1: Potential sources of energy harvesting](image)

Solar energy harvesting is the most promising candidate as a harvesting source, since it offers the highest energy density, among the other options. Also solar cells are the most mature and commercially established energy harvesting solution, and are available in a wide range of sizes and power levels [14][16]. In [17], a solar energy harvesting module is used to power a sensor mote. Here, the solar energy establishes a topology changing over time (based on which sensors are currently being powered), where some nodes can receive and transmit packets without consuming the limited battery resources in [18]. In [19], a solar energy harvesting scheme which works on the principle of photo-voltaic effect is proposed. Besides this scheme, a new recharging circuitry, which can reinforce the lifetime of the nodes, is designed to recharge the battery of the nodes when the charge drops below a threshold.
level. [20] proposes a harvester which utilizes the automatic maximum power point tracking at a minimum energy cost by minimizing the size of harvester’s photovoltaic modules. The proposed harvester’s power consumption is less than 1 mW. In [21], the authors proposed a new low-power Maximum Power Point Tracker (MPPT) circuitry for wireless sensor network which transfers the energy in non-optimal weather conditions. Additionally, there are implementation of solar energy harvesters as an integrated circuit. The integrated solar energy harvester presented in [22], scavenges the energy by using array of photo-diodes, fabricated with storage capacitors on a chip. In spite of above mentioned benefits of solar harvesting, it also has a drawback of being able to operate only when direct sunlight is present.

Another source of energy harvesting is mechanical vibration. A vibrational energy harvester, presented in [24], scavenges electricity from the force exerted on shoes during walking by using piezoelectric crystals. An example demonstration of vibrational energy harvesting from the ambient environment is proposed in [25] to drive an autonomous wireless condition monitoring sensor system (ACMS). This system generates average 58µW in a volume of only 150mm³ at 52MHz, when the system is used with ACMS. With a pure resistive load, the system can generate 120µW at 1.7ms⁻² rms acceleration. This system is also commercialized as an industrial air compressor and an office air conditioning unit. In [26], the aim is to achieve higher than 10µW per day when the person wears the watch and moves the hand. The important aspect for vibrational energy harvesting is the size of the generator. [27] presents a mechanism to gather energy based on motion-driven generator with linear motion of the proof mass. According to the experiments, with 0.25mm³ generator, the device is able to generate power between 1 and 4µW. With an 8cm³ generator, the power between 0.5mW and 1.5mW is measured as an output. Apart from these works and research, many commer-

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration/Motion</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>4µW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>100µW/cm²</td>
</tr>
<tr>
<td>Temperature Difference</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>25µW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>1 – 10mW/cm²</td>
</tr>
<tr>
<td>Light</td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td>10µW/cm²</td>
</tr>
<tr>
<td>Outdoor</td>
<td>10mW/cm²</td>
</tr>
<tr>
<td>RF</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>0.1µW/cm²</td>
</tr>
<tr>
<td>WiFi</td>
<td>0.001mW/cm²</td>
</tr>
</tbody>
</table>

Table 2.1: Estimated power from various energy harvesting sources
cial motion-driven energy harvesters are already being used in industrial applications. These devices are capable of harvesting in tens of mW \cite{28}, \cite{29} with the price of the devices’ size being proportional to the energy harvested.

Small sensors and on-body devices can also be powered with human body energy harvesting. One of the approaches is to power devices from human body heat. According to \cite{30}, the first thermoelectric device utilizing this concept was demonstrated in 2004. Interuniversity Microelectronics Center (IMC) fabricated a watch-size thermoelectric generator, which can scavenge energy by using human body heat. The device generates about 100\(\mu\)W under normal activity. IMEC has also developed a wearable (headphone type) battery-less wireless 2-channel electroencephalography (EEG) system, which is powered by heat and ambient light. This system can generate more than 1mW, on average, in an indoor environment while consumes only 0.8mW \cite{31}. Recently, the research community has started to focus on improving efficiency of these thermoelectric devices. In a recent study presented in \cite{32} \cite{34}, thermal impedance matching as well as electrical impedance matching are two important aspects of improving the performance of thermoelectric devices affixed on the human body.

The concept of Wireless Power Transmission (WPT) is not new but was proposed by the famous scientist Nikola Tesla back in 1899. His experiments with the WPT device consisted of a massive coil connected to a high mast ball on its top \cite{4}. Based on Tesla’s research, W.C. Brown introduced and developed the first “rectenna”, which is a type of voltage rectifying antenna in 1960s. The first experimental results on the rectenna in 1963 reveal an efficiency of 50\% and output 4WDC and 40\% at output 7WDC by using 2 – 3GHz as the operational frequency. Moreover, he and his team also developed many devices based on Microwave Power Transmission (MPT) from 1964 to 1975, such as using MPT in helicopters and design of further refined rectennas whose efficiencies ranged from 26.5\% at 39WDC to 54\% at 495WDC with ampliton, an oscillator(or a generator of microwaves) which can amplify a broad band of microwave frequencies, at 2.45GHz \cite{35}.

Recently, many researchers have focused attention on RF energy harvesting, despite its low energy density. A wireless battery charging system using RF energy harvesting was studied in \cite{39}. In the study, a cellular phone can be charged with the charging rate of 4mV/second at a frequency of 915MHz. RF energy harvesting with ambient sources is presented in \cite{40}, where the energy harvester can obtain 109\(\mu\)W at 800MHz from daily office worker’s routine in Tokyo. A new design for remote telemetry based on RF energy harvesting was proposed in \cite{36}. The design is capable of generating and delivering RF energy for down-hole telemetry systems ,that is used for monitoring level of underground water and fossil fuels sources, by using conductive pipes radiating RF signal. Consequently, the down-hole telemetry systems may be converted to wireless systems with the help of this design. RF energy harvesting systems are also used with other common energy harvesting
systems for some critical life-support purposes. In [37], the authors presented a new harvester design which is based on a dual-source power scavenging and management system for ultra low power wireless medical applications. The approach provides a regulated 1.5V as an output voltage, with a total power consumption of less than 8µW and 48µW in sleep mode and operating mode, respectively.

Figure 2.2: Apparatus for ambient RF harvesting experiment, courtesy of [39]  
Figure 2.3: Temperature and humidity meter by using only ambient RF power [39]

In [38], the energy of 60 µW is harvested from TV towers, 4.1 km away, and is able to operate a small electronic device. The setup is shown in Figures 2.2 and 2.3. Ambient RF energy harvesting with two systems has been studied in [47]. The first is broadband system without the impedance matching network while the second is narrow band with the impedance matching network. The preliminary results indicate that the harvested energy is not sufficient to directly power the devices, but could be stored for later use. Many efforts have been focused on the design of RF energy harvesting circuit. In [44] and [48], an integrated circuit for RF energy harvesting at 868.3MHz, implemented in a Silicon-on-Glass substrate transfer technology, are presented. The RF-DC power conversion system was designed in [49], with 0.25µm CMOS technology. At the distance of 15 meters, 1 volt DC is measured with 0.3µA load current at 906MHz. In addition, the study presented in [50] mentions the comparison of the performance of voltage multipliers based on CMOS and Schottky Diode in RF energy harvester.

Common areas where RF energy harvesting concept is utilized include passive radio
frequency identification (RFID) and passive RF tags. RFID and RF tags contain a device powered by propagating RF waves [51]-[52]. In [56], 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 [41], [42], as well as commercial products have been introduced by the industry [53]. However, as we shall show in this thesis, this product (called as Powercast lifetime power evaluation and development kit) does not perform well in low power ambient RF environments, where the actual incident power level is 0 dBm and lower. Consequently, there is a need to develop an energy harvesting circuit that performs well under these realistic, low power conditions.

The proposed RF energy harvesting circuit is based on the voltage multiplier circuit, 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 [23]. A basic schematic of a Villard voltage doubler, sometimes also called Cockcroft-Walton voltage multiplier, and Dickson voltage multiplier are shown in Figure 2.2 and Figure 2.3, respectively. According to [44], Both Villard and Dickson topology reveal no significant difference in performance.

With these basics now established, we delve deeper into our proposed design in the next section.
Chapter 3

Dual-Stage RF Energy Harvesting Circuit

The main challenge faced in harvesting RF energy is the free-space path loss of the transmitted signal with distance. The Friis transmission equation (3.1) relates the received ($P_r$) and transmitted ($P_t$) powers with the distance $R$ as:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$  \hspace{1cm} (3.1)

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 \[43]. Even at this highest setting, the received power at a moderate distance of 20 m is attenuated down to only 10 $\mu$W. The efficiency of RF energy harvesting system (in percentages) defined with $\eta$ is also directly related with rectified power ($P_{dc}$) as well as dependent on received power ($P_r$) as seen on Equation 3.2.

$$\eta = \frac{P_{dc}}{P_r} \times 100$$  \hspace{1cm} (3.2)

In order to get high efficiency from the energy harvester, the rectifier circuit needs to be carefully designed by considering all its input parameters. Note that the rectified power
is dependent on the rectifier output voltage and current \( P_{dc} = V_{output} \times I_{output} \), and the number of stages influences greatly both the voltage and current drawn through the load. In the following sections, we detail the methodology for the new circuit design. We classify the stages of the work as follows:

- Selection and Effect of the Circuit Components
- Optimization Framework
- Simulation Results
- Fabrication
- Performance Evaluation

### 3.1 Selection of Circuit Components

As mentioned earlier, the new approach to RF energy harvesting circuit design proposed in this work is based on the voltage rectifier circuit. In this subsection, we explain how to select the components of voltage rectifier according to the constraints posed by the load, and also how the components of circuit influence the efficiency and performance of the circuit.

#### 3.1.1 Choice of Rectifier Topology

As mentioned in [44], the rectifier topologies do not demonstrate a significant difference in performance. Hence, the Dickson topology (Figure 2.5), which has a parallel configuration
of capacitors in each stage is chosen. The advantage here is that because of its the capacitors connected in parallel, the effective circuit impedance is reduced. Hence, this makes the task of matching the antenna side to the load side simpler.

![Figure 3.2: Dickson diode based multiplier](image)

Figure 3.3: Dickson CMOS based multiplier

After choosing the Dickson topology, we next focus on the individual components that compose each stage. The factors we consider here are component’s price, its operating performance and response curve at the RF frequency, and its electrical specifications. We assert that diode technology is a better choice instead of CMOS technology in light of the above considerations (Figure 3.3). As a result, Dickson diode based rectifier topology (Figure 3.2) is selected in this work.

### 3.1.2 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 Ω antenna, the −20 dBm received RF signal power means an amplitude of 32 mW. As the peak voltage of the AC signal obtained at the antenna is generally much smaller than the diode threshold [44], 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 0.15V.

![Figure 3.4: HSMS-28XX Schottky Diode](image)

We employ 2 different diodes from Avago Technologies, HSMS-2822 and HSMS-2852. The former has the turn on voltage of 340 mV while the latter is at 150 mV, measured at 1 mA and 0.1 mA, respectively. Consequently, HSMS-2852 is suitable for low power design (LPD) used in the weak RF environment, while HSMS-2822 is preferred for high power design (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.

### 3.1.3 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 3.5 and figure 3.6 show 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 $20 \text{ dBm}$ 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.

### 3.1.4 Effect of Load Impedance

Figure 3.7: Effect of load impedance on the efficiency of energy harvesting circuit
It is important that the load impedance is carefully selected for a specific energy harvesting circuit, whose impact on the circuit performance can be seen in Figure 3.7. 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 $1 \Omega$ to $181 \Omega$ 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 micro-controller 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 state to consume $30 \mu A$ at $3.0 \text{ V}$, which translates to a $100 \Omega$ resistive load. A $100 \Omega$ resistive load is further used in our optimization.

### 3.1.5 Effect of RF Input Power

![Figure 3.8: Effect of RF input power on the impedance of the energy harvesting circuit](image)

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 a particular input power. Figure 3.8 depicts the effect of RF input power, ranging from $-20 \text{ dBm}$ to $20 \text{ dBm}$, on the impedance of the energy harvesting circuit. The non-linearity in operation is shown by a sharp bend at $5 \text{ dBm}$. 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 $-20 \text{ dBm}$ to $20 \text{ dBm}$, subject to several device and performance constraints. The conversion efficiency is defined in [46] as,

$$\eta_c = \frac{\text{DC Output Power}}{\text{Incident RF Power} - \text{Reflected RF Power}},$$  \hspace{1cm} (3.3)

whereas, the overall efficiency is given by:

$$\eta_o = \frac{\text{DC Output Power}}{\text{Incident RF Power}}$$  \hspace{1cm} (3.4)

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 $-20 \text{ dBm}$ to $20 \text{ dBm}$ into two.

Conversion efficiency does not take impedance mismatch into the 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 according to this reason, which is the sum of two curves on either side of the crossover point.

Figure 3.9 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
Figure 3.9: Efficiency curves of two energy harvesting sister-circuits, for LPD and HPD
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 3.9, there are $(\beta-\alpha)$ 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,

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

(3.5)

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

$$\gamma = \arg \max_{\gamma} \{ \int_{\alpha}^{\gamma} f_1(x) \, dx + \int_{\gamma}^{\beta} f_2(x) \, dx \}$$  

(3.6)

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 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.

(3.7)

**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:

\[ \forall \alpha : f(x) = f(L, C) \quad (3.8) \]

Consequently, the equation \([3.6]\) becomes,

\[ \gamma = \arg \max_{\gamma} \left\{ \int_{\alpha}^{\gamma} f_1(L, C, x) \, dx + \int_{\gamma}^{\beta} f_2(L, C, x) \, dx \right\} \quad (3.9) \]

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 \([3.9]\) becomes,

\[ \gamma = \arg \max_{\gamma} \left\{ \int_{\alpha}^{\gamma} f_1(N_1, L, C, x) \, dx + \int_{\gamma}^{\beta} f_2(N_2, L, C, x) \, dx \right\} \quad (3.10) \]

We can construct the general optimization framework as follows:

**Given :** \(L, C, N\)

**To find :** \(\gamma, N_1, N_2\)

**To Maximize :**

\[ \text{Area}_{\text{total}} = \int_{\alpha}^{\gamma} f_1(N_1, L, C, x) \, dx + \int_{\gamma}^{\beta} f_2(N_2, L, C, x) \, dx \quad (3.12) \]

**Subject to :**

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

\[ \int_{\gamma}^{\beta} f_2(N_2, L, C, x) \, dx > \int_{\alpha}^{\gamma} f_2(N_2, L, C, x) \, dx \quad (3.13) \]
\[ \int_{\gamma}^{\beta} f_2(N_2, L, C, x) \, dx > \int_{\alpha}^{\gamma} f_2(N_2, L, C, x) \, dx \quad (3.14) \]

\[ \forall \, x : I(x + \Delta x) \geq I(x) \quad (3.15) \]

\[ \forall \, x : V(x + \Delta x) \geq V(x) \text{ and} \quad (3.16) \]

\[ V(x = -10) \geq 1.8 \, V. \quad (3.17) \]

Figure 3.10: Optimization Constraints

The aim of this optimization framework is to maximize area under the joint efficiency curve throughout, subject to several constraints which are explained below as seen on Figure 3.10:

- 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 \(-20 \, \text{dBm} \geq 1.8 \, V\). 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.
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.

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 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 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 3.11. 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.

![Figure 3.11: Efficiency comparison at 10.75 dBm for different sub-circuit stages](image-url)
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 3.12. 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.

![Efficiency curves and normalized area values](image)

Table 3.2: Optimal solution at various crossover points

<table>
<thead>
<tr>
<th>Sub-circuit/Area</th>
<th>5 dBm</th>
<th>10.75 dBm</th>
<th>15 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPD</td>
<td>5-stage/1268.209</td>
<td>7-stage/1550.420</td>
<td>9-stage/1767.046</td>
</tr>
<tr>
<td>HPD</td>
<td>10-stage/886.416</td>
<td>10-stage/745.355</td>
<td>8-stage/482.067</td>
</tr>
<tr>
<td>Total area</td>
<td>2154.625</td>
<td>2295.775</td>
<td>2249.122</td>
</tr>
</tbody>
</table>

Table 3.1: Normalized area at 10.75 dBm crossover point

Through an exhaustive search following the constraints of our optimization framework, we find that the 7-stage 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 Table 3.2 and Figure 3.12 respectively.
Figure 3.13: Efficiency of optimized energy harvesting circuit and WISP

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) \cite{54}. 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 \cite{54}. 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 3.13 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 3.14. The energy harvesting circuit yields the output voltage of 2.074 V at $-10$ dBm. \cite{45} has stated earlier that the Mica2 sensor mote is able to operate at 1.8 V. This output voltage of energy harvesting circuit at $-10$ dBm is sufficient to fully operate the Mica2 sensor mote, once the energy storage is sufficiently charged. Moreover, at $-7$ 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

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 modelled with ADS and vendor supplied component libraries.

Figure 3.15: Voltage comparison of ideal and non-ideal circuit with PCB effect
The voltage and efficiency comparison between ideal circuit and non-ideal circuit with PCB effect are shown in Figure 3.15 and Figure 3.16, respectively. The effect of non-ideal components and PCB becomes clear as the received RF input power goes beyond $-16$ 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.

![Graph](image)

**Figure 3.16: Efficiency comparison of ideal and non-ideal circuit with PCB effect**

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 3.17 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 3.18 and Figure 3.19 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.
Figure 3.17: RF energy harvesting with multiple antennas

Figure 3.18: Effect of multiple antennas on EH circuit’s voltage
Figure 3.19: Effect of multiple antennas on EH circuit’s efficiency

The final fabricated PCB of our proposed energy harvesting module connected to a Mica2 mote is shown in Figure 3.20. 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.

Figure 3.20: RF energy harvesting circuit prototype
The energy harvesting circuit prototype is tuned to match simulation parameters using Agilent E5061B vector network analyser. 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 $\mu$A 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 3.4: Parameters used in PCB fabrication for Dual-Stage circuit design

<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 3.3: Components used in ADS simulation for Dual-Stage circuit design

<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>

3.5 **Performance Evaluation**

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 [53]. 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 3.21 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.

![Graph](image)

Figure 3.21: Output voltage comparison of simulation, prototype and Powercast energy harvesting circuit

Figure 3.22 depicts comparison of output voltage plots of our prototype in LPD region against 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 $3.3\,\text{V}$. 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 $3.3\,\text{V}$.

![Graph](image)

Figure 3.22: Output voltage comparison of simulation, prototype and Powercast energy harvesting circuit
Figure 3.23: Efficiency comparison of simulation, prototype and Powercast energy harvesting circuit

Figure 3.23 shows the efficiency comparison of non-ideal simulation, prototype and Powercast P1100 across the load of 100 KΩ with −20 dBm to 20 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 Micro-controller (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 [55]. 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 of our circuit is not only limited to powering sensors directly but also trigger charging, energy neutral operation and radio wakeup [50]. 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 [57] 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.
Chapter 4

RF Energy Harvesting Circuit Design

For Wake-up Radio

This chapter describes the adaptation of our previously designed RF energy harvesting circuit, which works in parallel with the Wireless Identification and Sensing Platform’s (WISP’s). The WISP acts as the basic wake-up radio, which triggers an interrupt to the Tmote Sky mote, the main communicating sensor node. The parameters that influence selection of the circuit components and design strategies for efficiency in performance are described here.

Our aim here is to allow our harvesting circuit to enhance the wake-up ability of the WISP, by increasing the power range. According to data obtained from UoR, this power range is between $-20$dBm and $0$dBm, which we have already classified earlier as the low power region. Thus, we select the low power design (LPD) circuit design based on Dickson diode based rectifier for interfacing with WISP. Along similar lines, we select HSMS-2852 Schottky diode as the rectifier diode component. We consider 10 stages for circuit to ensure sufficient output voltage of the circuit to drive the Tmote at 915MHz. The circuit is fabricated on the PCB according to the data summarized in Tables 4.1 and 4.2.

In order to get high voltage and power from the circuit output, we must consider the impedance matching between the antenna and the proposed circuit to provide power transmission. The optimization framework here has several points of departure from the earlier case used in conjunction with the Mica2 mote. The aim of the new optimization framework would be to maximize the output voltage of the energy harvesting circuit throughout the

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2In this study, we collaborate with the research group in Electrical Engineering department at University of Rochester (UoR)
Table 4.1: Components used in ADS simulation for circuit design of wake-up radio study

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage capacitor</td>
<td>36 pF</td>
</tr>
<tr>
<td>Diode</td>
<td>HSMS-2852</td>
</tr>
</tbody>
</table>

Table 4.2: Parameters used in PCB fabrication for circuit design of wake-up radio study

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<thead>
<tr>
<th>Component</th>
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<tr>
<td>Dielectric constant</td>
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</tr>
<tr>
<td>Through-hole size</td>
<td>29 mil</td>
</tr>
</tbody>
</table>

range of $-20 \text{dBm}$ and $0 \text{dBm}$, subject to the constraint that the output voltage value of circuit should give the peak value exactly at 915MHz, and also it should be continuous and monotonically increasing.

In the optimization framework, we keep the input RF power fixed and observe the resulting changes on the output voltage value while sweeping the inputs frequency of the circuit. After we determine the frequency at which the output voltage value reaches the peak value, we add the capacitor and inductor components on the matching network part as series and parallel, respectively, to change the frequency of the peak response and draw it closer to 915MHz. In order to sweep the frequency and provide the fixed input RF power to circuit, Agilent N5181 MXG RF signal generator is used (Figure 4.1). We also use a Agilent 34401A multimeter to measure the output voltage of circuit (Figure 4.2).

Figure 4.1: Agilent N5181 MXG RF Signal Generator

Figure 4.2: Agilent 34401A multimeter

In order to provide power transmission without any waste of energy, we try to determine the components of an efficient matching network. We vary the value of the capacitor from 0.1pF to 10pF with 0.1pF step size. Similarly, the value of the inductor is changed from 1nH to 10nH with 1nH step size. We first determine the frequency of peak output voltage with the unmatched circuit. Thereafter, we add the capacitor or inductor as a series component by starting from the minimum value from the determined range, and observe how the peak output voltage changes with the change in the frequency. When we find that the peak voltage is reached, and this frequency is closer to 915MHz, the component parameters such as value and type are used as the series component of the matching network.

After selection of the series component, we repeat similar procedure to find the proper component values for parallel connections of the matching network. These iterations finally result in the peak voltage being attained at a frequency very close to 915MHz. At this point, we assume that all components of the matching network are correctly determined. Table [4.3]
summarize the data about the components used to build the energy harvester. The final fabricated version of the proposed circuit is shown in Figure 4.3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series Capacitor</td>
<td>0.1 $pF$</td>
</tr>
<tr>
<td>Parallel Capacitor</td>
<td>1.0 $pF$</td>
</tr>
<tr>
<td>Stage capacitor</td>
<td>36 $pF$</td>
</tr>
<tr>
<td>Diode</td>
<td>HSMS-2852</td>
</tr>
</tbody>
</table>

Table 4.3: The components used to build the energy harvester

After the fabrication of RF energy harvesting circuit, we compare the improvement in the wake-up performance of the combined circuit where the WISP-mote and the energy harvesting circuit work in parallel. The base case is the wake-up performance of the WISP-mote acting alone. The experimental results are obtained from the study conducted in the UoR’s campus, where our circuit is connected to a WISP-mote, which further triggers the Tmote Sky. The outputs of each stage are linked, as indicated in Figure 4.4. The voltage output of our proposed harvesting circuit is connected to the WISP’s voltage regulator input. This regulates the output voltages of WISP’s energy harvester that is eventually used to trigger the Tmote.

Figure 4.3: The Wake-up Study harvester circuit prototype

Figure 4.4: The combined prototype
For providing RF input power for energy harvesters, the apparatus involves Impinj Speedway RFID reader for WISP and Powercast 915MHz 3W transmitter for proposed energy harvesting circuit as seen in Figure 4.5.

WISP can trigger the Tmote-Sky for wake-up at most 18ft as seen in Figure 4.7. With help of the proposed energy harvester, WISP can easily trigger to mote at 19ft operation distance from RFID reader. As seen in Figure 4.7, the performance of combined prototype is better than the performance of WISP-mote. The proposed energy harvester reduces the charging time of WISP’s capacitor which is linked in voltage regulator input. Less charging time can enable quick wake-up. Due to this reason, the proposed circuit helps to reduce the response delay, known potential wake-up delay, by around 50%.

![Experimental Setup](image1)

Figure 4.5: The experimental setup for wake-up radio

![Voltage Output](image2)

Figure 4.6: Voltage output of WISP and power harvesting circuit

![Potential Wake-up Delay](image3)

Figure 4.7: Potential wake-up delay

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5The experimental setup and measurement results (Figure 4.6 and 4.7) are obtained from Professor Wendi Heinzelman’s research group in Department of Electrical Engineering at University of Rochester.
Chapter 5

Conclusion and Future Work

We show that with a simple yet optimal design and optimization, our 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 dBm). Moreover, the prototype is able to sustain the energy neutral of Texas Instruments’ MSP430G2553 in LPM4 at −20 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 dBm to 7 dBm. In addition to dual-stage RF Energy Harvesting Circuit, the prototype designed for Wake-up Radio Study helps to reduce communication delays between WISP and RFID reader by around 50%. The harvesting circuit also helps to increase the maximum access point of WISP from 18ft to 19ft. Finally, in order to have a performance improved and lower cost, the circuits need to be implemented as “System on Chip” as it suffers less above mentioned parasitics, and we will pursue this in our future work.
Bibliography


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