Ph.D. Thesis Proposal

Wireless Transfer of Energy Alongside Information:

From Wireless Sensor Networks to Bio-Enabled Wireless Networks

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May 29, 2012

Abstract

Despite their constant evolution over the last few decades, wireless communication networks still struggle with energy conservation. The problem manifests itself in many applications, in particular wireless sensor networks, where communications do not occur frequently and nodes often remain idle, and small-scale communication networks, whose nodes need to to be minuscule. Such applications can achieve optimal energy-efficiency using passive (battery-less) receivers that wirelessly receive energy and information at the same time. In this proposal, we present techniques to simultaneously deliver energy alongside information during wireless communications.

First, we present mechanisms to consolidate energy and information transfer in wireless sensor networks. We introduce iPoint, a communication system including a passive wireless receiver capable of establishing two-way communication with a commodity smartphone. We prototype and experimentally evaluate our design that includes techniques to ensure efficient delivery of energy and information and novel communication protocols.

In the second part of the proposal, we study energy and information transfer in bio-enabled wireless networks. These theoretical networks feature wireless communication between wireless nodes and tiny biological organisms. We introduce possible designs for such networks using several enabling technologies, and present theoretical results on the performance of energy and information transfer.

Contents

1 Introduction

Over the last decade, wireless communication networks have achieved major success and emerged as the key technology for enabling the mobile revolution. Providing mobility and accessibility, wireless communication redefines the notion of network and connectivity, and powers a huge range of applications. The speed, capacity and robustness of wireless communication keep improving everyday, but several challenges remain, energy-efficiency being one of the most notable [1, 2]. Conserving energy in wireless networks is particularly important, because the wireless nodes are critically dependent on their limited energy resource, that is, their battery. Receiving and decoding a wireless signal normally requires a significant amount of computations. In addition, transmitting wireless messages is one of the most energy consuming tasks in today's computing. Performing such energy-hungry tasks with low efficiency reduces the lifetime of the nodes and eventually causes node death degrading connectivity and performance of the network. Therefore, several attempts at hardware and software levels have been made to tackle this problem: More efficient batteries with larger capacities have been invented [3]; the power consumption of wireless nodes has been significantly reduced thanks to advances in low-power electronics and new methods of computation such as reversible computing [4]; finally, many energy-aware communication protocols and algorithms that factor in the energy constraints of wireless nodes have emerged [5, 6, 7, 8].

All wireless networks struggle with the energy conservation issue, yet the problem is more evident in certain applications such as Wireless Sensor Networks (WSN). A WSN usually consists of several spatially distributed nodes that monitor or sense a physical or environmental condition, and transmit the collected data via wireless communication. The sensing process generally does not require a lot of energy. In fact, wireless transmission accounts for almost all the node's energy consumption. In most cases, the data collection occurs sporadically or upon an external request. Therefore, continuous operation of a node's radio, which results in fast battery drainage, is not necessary. Current techniques rely on periodically waking the receiver up to synchronize and respond to the requests of a master node [9, 10]. These methods help conserve energy but are far from optimal. Ideally, the radio component of the sensor node should go into a full-sleep (idle) mode that consumes virtually no energy and wakes up only on external requests or events. This can be achieved by integrating a completely passive component that acts as a wake-up circuit and relay the external request to the idle node. The challenge of engineering such a system, which includes software, hardware and communication protocols, is one of the goals of this study.

Having a receiver that consumes *no energy* while being idle is the optimal solution for any of the scenarios mentioned above. Note that this goal can not be achieved by simply reducing the energy consumption of the radio components; rather, the energy consumption should be eliminated when no communication is taking place. This rules out the use of conventional wireless devices which are basically an ensemble of active electronic boards that consume energy while operating, regardless of how energy-efficient they are. Instead, let us consider the following scenario: Assume that the incoming signal, which carries a certain amount of information, provides the receiver with the energy required to extract the information. On the other end, the receiver simultaneously executes two actions on the signal. First, it converts the energy of the signal into a usable form. Second, it runs the decoding procedure to extract the embedded information. In this case the energy consumption occurs only when there is an incoming signal, and it is fully provided by the transmitter entity. Therefore, the receiver does not rely on any other source of energy.

Combining energy and information transfer is a promising approach that leads to engineering *passive* wireless receivers. There are many communication schemes that provide vast range of throughput, complexity and energy-efficiency. Also, a few mechanisms such as RF energy harvesting have been proposed to transfer energy wirelessly [11, 12]. However, combining these schemes presents several challenges. The range and capacity of today's energy transfer methods are very limited, which makes pairing them with normal communication methods difficult and often impossible. In order to have a functional system, we need to carefully optimize, modify or completely revamp the energy and information transfer mechanisms. This includes building more efficient systems using specialized hardware, and devising better algorithms software solutions that exhaust the physical limits of the hardware.

Another key factor that greatly impacts the energy conservation problem in wireless networks is the physical dimensions (size) of the wireless device. In context of conventional wireless communications, bigger dimensions normally translate to higher battery capacity hence longer lifetime. Also, larger systems can accommodate a larger antenna, which increases the antenna gain and subsequently the quality of both transmission and reception given a fixed energy budget. The problem of energy becomes more severe when the size of the system approaches micro and nano scales. In such extreme scales, devices are inevitably passive because they cannot afford to include a portable source of energy (i.e. battery). Providing a solution for energy problem at these limits is particularly important as it opens up exciting new avenues of possibility for wireless networks. Nanorobotics is one of the areas that could greatly benefit from the solution. Another potential outcome is the possibility to extend the scope of today's wireless communication from electronic devices to include interactions with biological systems. The second part of this research will focus on this aspect of the energy problem.

In the case of extremely small systems, the problem shows a radically different face. In such a small scale, there is no room for sophisticated electronic components. Furthermore, especially for biological systems, almost all the information is being exchanged by means of mechanical and biochemical signals, which are of an entirely different nature from electromagnetic signals. An efficient transduction mechanism is necessary to connect these two seemingly different worlds.

Proposed Research

In this work, we plan to explore several techniques to transfer energy alongside information via a wireless link. We classify our research into the two following studies:

- First, we look into techniques to consolidate the energy and information transfer in wireless networks. We review and compare the energy transfer technologies, provide design considerations and sketch guidelines to implement such functionality. At the end, we present a communication system that allows two-way communication between a commodity smartphone and a passive receiver. The system features a combination of ultralow-power electronics and RF energy harvesting. We introduce several techniques to increase the efficiency of the information and energy channels, propose novel communication paradigms and protocols optimized for our setup, build prototypes and finally evaluate the system performance experimentally. Section 3.3 presents detailed description of the system, our preliminary results and future work plan.
- The second part of our research, outlined in section 4, focuses on transferring energy and information to a tiny biological organism through a synthetic interface. We study the enabling technologies that allow us to build such an interface, challenges ahead and the fundamental limits for energy and information transfer. We propose to study two different approaches to transduce electromagnetic signals to biochemical signals. We provide theoretical results supported by simulation validations.

2 Related Work

In this section, we review the related work and research that has been trying to solve the same problem.

RFID tags have the potential to deliver information anytime, anywhere [13, 14]. However, RFID tags have significant limitations making them impractical for delivering a substantial amount of information to commodity smartphones. First of all, equipping smartphones with an RFID reader is a significant and challenging modification to the phone hardware. Secondly, among the three types of RFIDs (i.e., passive, active, and semi-active), only the passive ones do not require a battery and therefore satisfy severe longevity constraints. However, passive RFIDs require the readers to transmit at high power (in the order of watts), with large antennas. Furthermore, such RFIDs are only capable of storing a very limited amount of information (e.g., 128 bytes) and are not capable of sophisticated interactions.

Recently, a clever alternative solution to RFID tags and traditional barcodes, called bokode, was developed to deliver information from a dot of 3 millimeters diameter encapsulating a high density Data Matrix code [15]. The information is revealed by putting an off-the-shelf camera in an out of focus mode. This solution has the advantage to reduce the size of the tag and increase the information density but still keeping the tag passive. However, bokode still lacks a two-way communication capability and requires sophisticated digital cameras (10Megapixel with a large lens) with in/out focus capability. In the future, if smartphones become equipped with controllable focus cameras, the envisioned iPoint system might benefit from integrating a bokode-based LCD display to deliver information to a smartphone at a lower energy cost.

Several RF-energy harvesting techniques and prototypes were explored over the last few years. The WISP platform and its variants harvest energy from RFID reader [16], TV radio stations [17], and are capable of powering a ultralow-power microcontroller. The WISP was also used as a batteryless sensor node to communicate with a traditional RFID reader [16]. It relies on a high energy sources (30dBm) operating at a medium RF frequency (915MHz). The constraint of the iPoint to operate on the low RF energy from smartphones (few dBm) and higher WiFi frequency (i.e., 2.4GHz) requires more advanced RF-energy harvesting mechanisms that we present in the next sections. Other platforms for wireless power transfer exist but require either high transmission power on the 915MHz band [18], or require highly customized transmitters and receivers such as in wireless power transfer via strongly coupled magnetic resonances [19].

While fully operational bio-enabled wireless devices are still a research dream, progress in several fields is making their components more plausible. Recent research has shown that it is possible to manipulate and control cell function, in vitro and in vivo, with an external magnetic field [20, 21, 22, 23, 24, 25, 26, 27, 28]. This is achieved by binding Magnetic Nano-Particles (MNP) to the surface of cells, and applying a static magnetic field to either twist (torque) or pull the MNP. An FM/AM controlled cell excitation was also shown to propagate through from cell to cell as inter-cellular Ca^{2+} waves [29]. Other researchers have shown that it is possible to down-convert an RF signal to a very-low few frequency torque of a magnetic nano-particle ($\sim$ 3Hz) [30]. The computer and networking community have been investigating various molecular computing and communications paradigms obtaining theoretical results, defining frameworks, and designing novel mechanisms for bio-enabled communications [31, 32, 33, 34]. The synthetic biology community has been making steady progress on designing, programming and standardizing biological systems [35]. For example, a class of stochastic chemical reaction networks was recently shown to be Turing universal and can therefore compute any computable function. Digital memory biological devices were successfully designed from transcriptional networks. Biological bi-stable switches were also successfully engineered. Finally, progress has been made in understanding extremophile bio-organisms, which thrive in extreme environments from $-273°C$ to $+151°C$, tolerate over 1,000 times more radiation than other organisms [36], and can be used as a chassis for synthetic biology.

3 Consolidated Energy and Information Channels in Wireless Networks

In this part of our research, we aim to study techniques to combine energy and information transfer channels in wireless networks. We consider a wireless sensor network whose nodes (devices) perform computations electronically and communicate using Radio-Frequency (RF) signals. In order to eliminate the energy conservation problem, the receiver may not rely on a battery or other unpredictable source of energy, such as solar energy or mechanical vibrations. We propose to design a system in which the receiver obtains the energy required to receive and decode the transmitted signal from the signal itself. Similar to many WSN models, this system includes two types of nodes: passively-powered receivers, and energy-provider *master* node.

3.1 Energy Transfer Mechanisms

Mechanisms to transfer energy from a power source to a wireless device fall into two categories:

- Methods based on electrodynamic induction use inductive coupling between the source and the device, and provide high-efficiency energy transfer over very short distances, usually less than the dimensions of the inductive component. The efficiency declines significantly over greater distances, which makes such methods ineffective when the signal is high-frequency and long-range, a typical case in communications. Recently developed methods apply resonant inductive coupling to achieve much higher efficiency over longer ranges.
- Methods based on electromagnetic radiation, also called RF energy harvesting, include receivers equipped with *rectenna*, a specialized component made of an antenna connected to a voltage rectifier that converts energy of the electromagnetic energy of the received signal to a usable DC voltage. These methods attain longer ranges, but exhibit a number of limitations. At the antenna level, a system using omnidirectional antennas shows a quadratic drop in efficiency with respect to the distance. Moreover, the losses due to imperfect rectification and antenna matching reduce the efficiency of the system. Matching and rectification losses can be minimized in a well-designed rectenna. Also, the antenna efficiency improves by using directional antennas and applying beam forming techniques.

3.2 Design Considerations

RF energy harvesting allows the use of high frequency signals and does not limit how information is embedded in the signal, therefore meshes well with communication schemes. Nevertheless, the following design considerations should be taken to account:

- The amount of energy provided by RF energy harvesting is very limited. Thus, the receiver should consume as little energy as possible while operating.
- The receiver needs to obtain a minimum amount of energy before it can demodulate the information. Therefore, the signal should include a *preamble* designed to provide the energy to start-up the receiver.
- Having received the signal, the receiver continues to process and respond to the request. The receiver should have already harvested enough energy to complete the tasks, otherwise the signal needs to include a *trail* that provides the required energy and may contain no actual information.
- Because of severe energy constraints, the demodulation process should be as simple as possible, while remaining effective. Sophisticated decoding mechanisms demand a significant amount of computations and energy, hence are not optimal.

Most of today's communication protocols do not fulfill the requirements mentioned above, thus need to be accordingly modified or revamped. In the following section, we present a system that employs a two-way consolidated energy and information channel. The system includes two optimized communication protocols to achieve maximum energy efficiency.

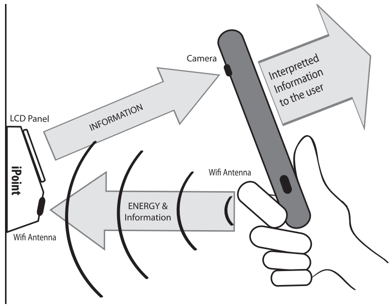


Figure 1: Conceptual illustration of how iPoint device performs.

3.3 Energy Transfer and Communication between A Passively-Powered Device and A Commodity Smartphone

In this section, we propose a system provides two-way communication between a receiver with no source of energy and a conventional smartphone. We present a complete design of the system featuring energy harvesting as the energy transfer method. We explore various technologies, introduce new communication paradigms and build a prototype of the passively-powered device that we call *iPoint*.

3.3.1 Approach

A smartphone is an ultimate example of a wireless device. It provides a remarkable combination of data acquisition, computing power and communication interfaces, all in a highly portable package. Our design exploits such capabilities of the smartphone to mitigate energy conservation issues.

In the process of designing the iPoint, in addition to considerations stated in section 3.2, we focused on the following key characteristics:

- *Universality:* any smartphone, equipped with the commonly available WiFi interface and camera, should be able to serve as the master node without any hardware modifications. Installing a software application should be sufficient to enable all desired functionalities.
- *Interactivity:* the device should be able to accept, process, and reply to specific requests. In other words, the communication between the iPoint and the smartphone is bidirectional.

These defining features lead us to a design that introduces innovative communication paradigms and techniques and the integration of a set of fairly unrelated technologies. In the following, we briefly review the system hardware and software architecture, the components, and the communication paradigms and techniques:

- *iPoint components:* the iPoint consists of a rectenna optimized for the 2.4GHz WiFi band, an ultralow-power microcontroller with an LCD-driver and an multi-segment LCD panel.
- *Smartphone:* virtually any smartphone with a WiFi network interface and an integrated camera.
- *Energy-provisioning:* the smartphone delivers the energy to the ipoint via WiFi transmission. The iPoint benefits from a more efficient RF energy harvesting circuit optimized for limited transmission power of smartphones, about two orders of magnitude less than conventional RFID readers.
- *Multimodal communication:* we propose two novel communication mechanisms to circumvent the severe energy asymmetry and constraints. 1) The information from the smartphone to the iPoint is encoded in the WiFi packet width, which results in much simpler and more energy efficient demodulation at the expense of a lower datarate. 2) The information from the iPoint to the smartphone is encoded as a series of patterns shown on the LCD, to be captured by smartphone's camera.

3.3.2 System Architecture

This section outlines the architecture of the proposed system. We describe the system components in detail, discuss the required features, important parameters and trade-offs, and compare design choices. We break down hardware of the iPoint into three components: A rectenna that receives the information and energy, an ultralow-power computing core to process the data, and a display to show the outputs.

Rectenna The rectenna serves as the power supply for the device. Its two main components, the antenna and the rectifier circuit, in addition to two auxiliary circuits are described below:

- *Antenna:* The antenna is designed for the 2.4 GHz band. External whip antennas provide larger gain and better performance, whereas the integrated printed antenna make more compact design possible. The directionality of the antenna may be adjusted to achieve larger gain given spatial coordinates of the antenna with respect to the smartphone.
- *Rectifier circuit:* It converts the RF energy of the arrived WiFi signals to DC voltage by passing them through a cascade of voltage multiplier circuits. Input power of the rectifier is often extremely small, therefore a multi-stage rectifier is used to build up sufficient output DC voltage, normally 1∼5 V, to power the computing unit. The efficiency of the rectifier depends on the overall design of the circuit as well as electrical characteristics of its components, notably forward voltage of the diodes and leakage of the capacitors. A full-wave rectifier shows better converting efficiency and produces more stable DC output compared to a half-wave rectifier, but requires a differential output design. Designs using Schottky diodes, which have smaller forward voltage, and RF optimized capacitors show significantly better performance.
- *Matching circuit:* The antenna and the rectifier should be carefully matched over the WiFi frequency band. Matching is typically done by experiment. The trade-off between a good match and bandwidth of the rectenna should be considered in the design. The ideal bandwidth of the system is roughly 20 MHz, equal to width of the WiFi channel.
- *Regulatory Circuit:* A shunt voltage regulator is placed after the rectifier to maintain the output DC voltage level within the safe range of operation for the computing unit.

Additionally, the rectenna constructs the envelope waveform of the arriving WiFi transmission and passes it, as partially demodulated data, to the computing unit for further processing. We will discuss this in greater detail in section 3.3.3.

Computing Unit The computing unit of the iPoint should provide extremely low power consumption along with moderate computing capacity in a simple hardware design. Therefore, ultralow-power Micro-Controllers (MCU), such as TI MSP430 family, are a favorable design choice. The MCU should provide an adequate I/O interface and preferably include integrated drivers for external displays. Considering the energy constraints, the MCU may be underclocked to further reduce the power consumption.

Display The iPoint displays the information with sufficient contrast and clarity to guarantee error-free pattern recognition by the smartphone, and minimize the energy consumption of the process. Liquid Crystal Displays (LCD) require very small amount of energy to reach desirable contrasts, therefore are a better choice compare to LEDs. Given the same input voltage and distance from the camera, larger panels produce more pixels but less contrast compare to smaller panels.

Smartphone component To preserve universality of the system, no hardware modification is made on the smartphone. A software application, installed on the phone, provides all the functionality. The application allows user to send different requests to the iPoint, processes the information received from the device, and interpret the information for the user. The application obtains moderate control over the WiFi and camera interfaces via provided APIs.

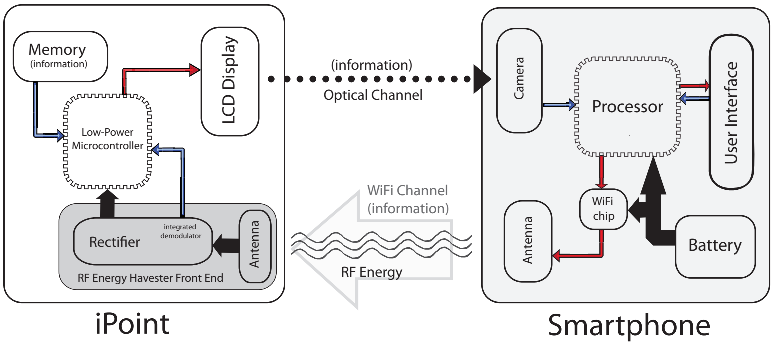


Figure 2: Detailed diagram of iPoint.

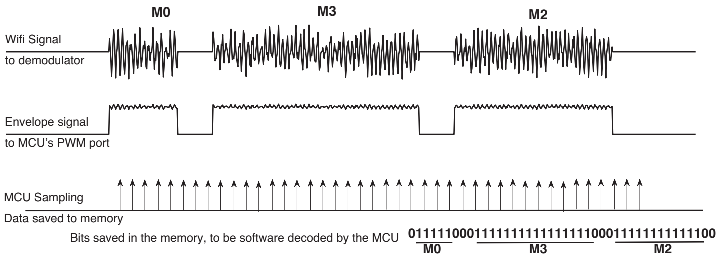


Figure 3: PLM decoding.

3.3.3 Multimodal Communication Mechanisms

Because of the very low-power transmission of smartphones, the energy harvested by the rectenna is not sufficient to power a wireless tranceiver and use conventional communication schemes. In this section, we describe two novel schemes that allow two-way communications between the iPoint and the smartphone within such limited energy levels. These schemes leverage smartphone's capabilities to reduce the energy budget of the communications. We break down the communications into two separate channels: smartphone-to-iPoint (S2I), and iPoint-to-smartphone (I2S). We propose a different communication scheme for each channel.

Packet Length Modulation To provide energy for the iPoint device, the smartphone transmits WiFi signals. However, demodulating WiFi packets needs an active demodulator requiring energy beyond what iPoint harvester can obtain from the signals. We propose Packet Length Modulation (PLM), a scheme in which the information is embedded in the length of the WiFi packets. In PLM, each packet length represents a symbol in the code. A message is defined as a sequence of WiFi packets each representing its corresponding symbol. Note that the smarphone sends the packets via its WiFi interface, which uses the WiFI protocol and does not know about the PLM. The following modifications to existing WiFi protocol are necessary to implement PLM encoding functionality:

- Since a WiFi access point may not be available, the smartphone creates an ad hoc WiFi network.
- The iPoint lacks any WiFi tranceiver, hence no acknowledgment packet is sent back to the smartphone. Therefore, PLM uses broadcast packets to prevent unnecessary packet retransmission.
- The WiFi packet length depends on the size of the packet, rate of the communication, and fragmentation. To have a robust encoding, the WiFi interface should transmit at a fixed rate without using any rate-adaptation algorithm.
- Assuming the PLM mechanism uses M different packet lengths, each packet encodes $\log_2 M$ bits of information. The fragmentation threshold determines the maximum packet length, hence the number of the symbols, and should be set to the maximum.

All modifications above are made in the software; no hardware modification is necessary.

To decode the PLM signal, the iPoint retrieves the length of the received WiFi packets. First, the rectenna generates the envelope signal of the received WiFi packet, and sends it to the computing unit. The computing unit samples the signal, determines its length, and maps it to its corresponding symbol. Predefined start and stop flags can be used to distinguish the beginning and the end of a message. Figure 3 illustrates the steps of PLM decoding.

PLM Rate Analysis: Let M denote number of the packet lengths in the PLM. Assume the transmitter sends the packets at rate, R. Let S_{min} be the smallest packet size. S_{min} is determined by the MCU clock to guarantee packet detection and length estimation, and by the energy harvester efficiency and MCU energy requirements. We consider packets of size multiples of S_{min}, $S_{\text{i}} = i \times S_{\text{min}}$. Hence, the average size of the packet would be $S_{\text{avg}} = \frac{S_{\text{min}}+S_{\text{max}}}{2} = \frac{(M+1)}{2} S_{\text{min}}$. Further assume a message is a sequence of packets separated by *idle* periods of the length equal to S_{idle}. We can calculate the time needed to send a packet, T_{p} as following:

$$T_{\text{p}} = \frac{S_{\text{avg}} + S_{\text{idle}}}{R} = \frac{(M+1)S_{\text{min}} + 2S_{\text{idle}}}{2R} \tag{1}$$

Each packet encodes $\log_2 M$ bits of information. Therefore,

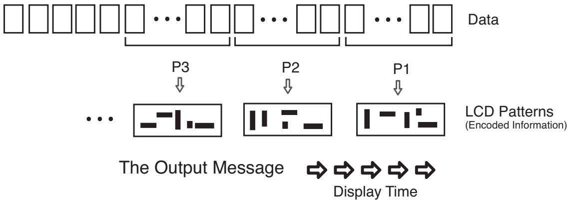


Figure 4: LPC Encoding for a M-segment LCD panel.

$$R_{\text{PLM}} = \frac{\log_2 M}{T_{\text{p}}} = \frac{2\log_2 M \times R}{(M+1)S_{\min} + 2S_{\text{idle}}} \tag{2}$$

The values of $S_{\min}$ and S_{idle} are determined by the maximum sampling rate of the MCU at iPoint side. Assuming f_{MCU} is the sampling frequency of the MCU, we have,

$$S_{\min}, S_{\text{idle}} > \frac{2}{f_{\text{MCU}}} \quad \text{(Nyquist theorem)}. \tag{3}$$

Hence,

$$\begin{aligned} R_{\text{PLM}}(max) &< \frac{2R\log_2 M}{(M+1)(\frac{2}{f_{\text{MCU}}}) + 2(\frac{2}{f_{\text{MCU}}})} \\ R_{\text{PLM}}(max) &< \frac{\log_2 M \times Rf_{\text{MCU}}}{M+3}. \end{aligned} \tag{4}$$

Note that during idle periods, iPoint does not receive energy from the smartphone. This lowers the output voltage of the rectifier which may result in unwanted shut-down of the system. To maintain the harvested voltage level above the desired threshold, $S_{\min}$ needs to be larger than S_{idle}. We define the duty cycle of the system as the $S_{\min}/S_{\text{idle}}$ ratio. The minimum duty cycle that allows the system to operate continuously depends on the implementation and may be evaluated experimentally. Moreover, $S_{\max} = M \times S_{\min}$ should be smaller than the fragmentation threshold in the smartphone's WiFi interface.

Finally, the smartphone needs to send preamble and trail WiFi packets to provide the energy required for the iPoint to startup, process the information and send the reply message back through I2S channel.

LCD Pattern Coding (LPC) The smartphone's transmitting power is much lower than a conventional RFID reader (few milliwatts for the smartphone versus few watts for the RFID reader). Therefore, using a similar scheme as passive RFID tags (i.e. back scattering) is not practical. Instead, we introduce LPC, a low cost way of sending information to the smartphone taking advantage of the imaging and computing capability of the phone. Having processed the request sent from the user, iPoint encodes the information in a series of LCD segment patterns and displays them on the panel. The smartphone captures the sequence of the patterns with the camera, recognizes the patterns, interprets the information, and finally sends the interpreted data to the user through its own UI. Because all the expensive operations are done on the smartphone side, the encoder/transmitter complexity of the iPoint may reduce significantly. This also proves to be a very energy efficient method as displaying information on the LCD panel requires far less energy compared to conventional back scattering scheme used in passive RFID tags. To get an intuition about the energy efficiency of LCD displays, one can think of the lifespan of wrist watches with LCD display; they run for years on a tiny button cell holding a small amount of charge.

An LCD pattern is a combination of the LCD display's segments where a segment can be ON or OFF. Upon receiving a request, the MCU computes the LPC encoded output message, as a sequence of predefined patterns to be shown on the LCD panel. An LPC message that consists of n patterns on a M-segment LCD panel, encodes $n \times M$ bits of information. At the other end of the channel, the LPC message is captured by the smartphone's camera by either recording a video or taking a series of pictures at a satisfying rate. The smartphone decodes the captured message by running a pattern recognition algorithm on each frame, and sends the interpreted data to the user via UI or uses the data in the next sessions of communication. An example of such setting is shown in Figure 5.

LPC Rate Analysis: The LCD pattern update rate can go up to 200 Hz. However, our experiments indicate that the deciding factor on an error free decoding is the sampling rate of the camera. Let R_c denote the maximum sampling rate of the smartphone's camera. Applying Nyquist theorem we have, $R_{\max} < R_c/2$ fps. Therefore, for a M-segment LCD display, we have the upper bound trasmission rate of $R_c M/2$ bps. For most of today's commercial smartphone cameras, $R_c \approx 30$ fps.

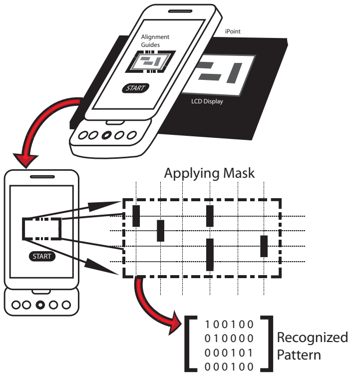


Figure 5: LPC decoding. To make decoding faster, the user is asked to align the image of the panel within a virtual box, then the frame is sampled only on the intersections of mask grid-lines (Narrow dashed lines).

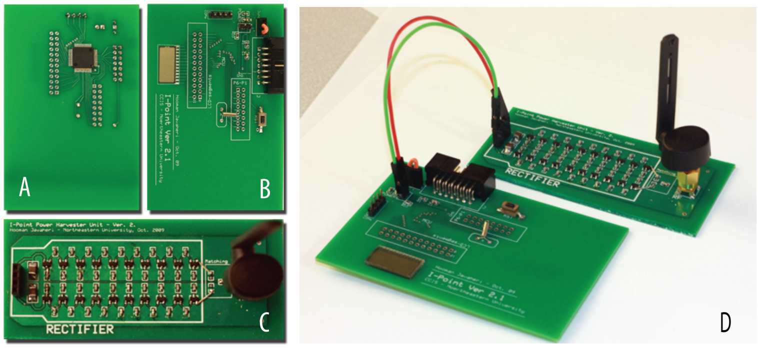


Figure 6: The iPoint prototype boards: A) Computing core upper layer (LCD display is shown). B) Computing core lower layer (MSP430 is shown). C) RF energy-harvester front end, 10-stage Greinacher voltage multiplier. D) The realization of iPoint version 2.1.

3.3.4 Prototype and Performance Evaluation

We prototyped different versions of the iPoint based on the design described in Section 3.3.2. The latest version (Ver. 2.1) is shown in Figure 6. In this section, we explain the implementation of the components in detail. In addition, several experiments are carried out in order to accurately characterize the prototyped device and prove the functionality of the design components. This section presents the detailed description of the testbed and experimental results.

Prototype

The smartphone used in the experiments is the *HTC Dream* also known as *T-Mobile G1* running Android mobile device platform Ver. 1.6. This 3G phone is equipped with a 528 MHz Qualcomm ARM11 Processor, 192 MB of DDR SDRAM, 320×480 pixel LCD Display with 180 ppi, 3.2 megapixel camera with auto-focus capability, and a WiFi (802.11 b/g) wireless interface [37]. We developed a software application in Android platform that sends multiple PLM-modulated requests, and performs the LPC decoding. The WiFi interface was configured to send broadcast packets at a fixed rate of 1 Mbps, the lowest rate supported by WiFi communication. Ideally, the application should create an ad hoc network, but the Android's support for the ad hoc mode is currently limited. As an alternative solution for prototyping, the smartphone connects to an auxiliary WiFi network created by an external access point. We use UDP/IP, as opposed to TCP/IP, to avoid unnecessary retransmissions caused by TCP flow-control mechanism. For the iPoint's rectenna, we implemented a 10-stage modified Greinacher circuit, a full-wave rectifier with parallel RF inputs connected to a 2.4 GHz whip antenna. We used high-performance low-leakage RF capacitors, and schottky diodes (HSMS-282 series from Avago technologies) with forward voltage threshold of 150∼200 mV, the lowest available. The value of intermediate capacitors were chosen experimentally to maximize the output DC voltage. The rectenna then was matched on WiFi channel 1 (2.412 GHz) using an LC matching network. The first stage of the rectifier circuit was used as an envelope-detector circuit for PLM decoding. For the communication core, we embed a TI MSP430F417, an ultralow-power microcontroller from Texas Instruments. This 16-bit flash MCU provides desired computing capabilities at low power consumption. It features 32 kB + 256 B of flash memory, 1 kB of RAM, Low supply voltage of 1.8 V, integrated LCD driver for 96 segments, on-chip comparator that can be used for finalizing the PLM signal demodulation, and very low active power consumption of 200 μA at 1 MHz, which makes it a reasonable choice for the iPoint prototype. The LCD panel selected for this generation of prototyped device was a 26 segment watch LCD display.

Experimentation Results

To characterize the efficiency of the rectifier circuit, a MXG Vector Signal Generator was used to feed the rectifier via a 0.5 feet coaxial cable, and the output voltage level of the rectenna was measured. The rectifier was fed with a WiFi signal in a wide range of input power, from -20 dBm to 15 dBm. The output voltage and efficiency were measured without a load and with a load of 140 kΩ, which is close to the MCU impedance in active mode. Rectifier shows efficiencies up to 72%. The results are shown in Figures 7a and 7b.

In order to test the functionality of the integrated demodulator of the front end, packets with different sizes were sent over the WiFi channel by the smartphone while the output of the energy harvester and integrated demodulator being measured. The rate of communication was fixed to 1 Mbps. The result is shown in Figure 7c.

To reduce the power consumption of the computing core, we aggressively underclock the MCU. The iPoint's computing core tasks, such as PLM decoding and LPC encoding, do not demand a very fast clock, hence the clock frequency may be reduced to a few kilohertzs. Figure 7d illustrates the results of our measurements of the MCU's power consumption running the same instructions at different clock frequencies.

Minimum duty cycle as one of the important characteristics of the iPoint system was discussed in section 3.3.2. We measured the output DC voltage of the rectenna for different duty cycles. The results are summarized in figure 7e.

The power consumption of two LCD panels with different sizes were measured: Panel 1 (3 cm^2, 24 segment), and Panel 2 (1.8 cm^2, 26 Segments). A test image was taken from the LCD panels at the same distance and under the same light environment while the same pattern were displayed on both panels. The contrast of the panels were compared digitally in Adobe Photoshop. To create a given desired contrast, we measured the required voltage and input current for each panel. The Larger panel, requires 2.9 V drawing 49 μA (142.1 μW), whereas Panel 2 requires 1.9 V drawing 21 μA (39.9 μW).

3.4 Improvement and Future Work

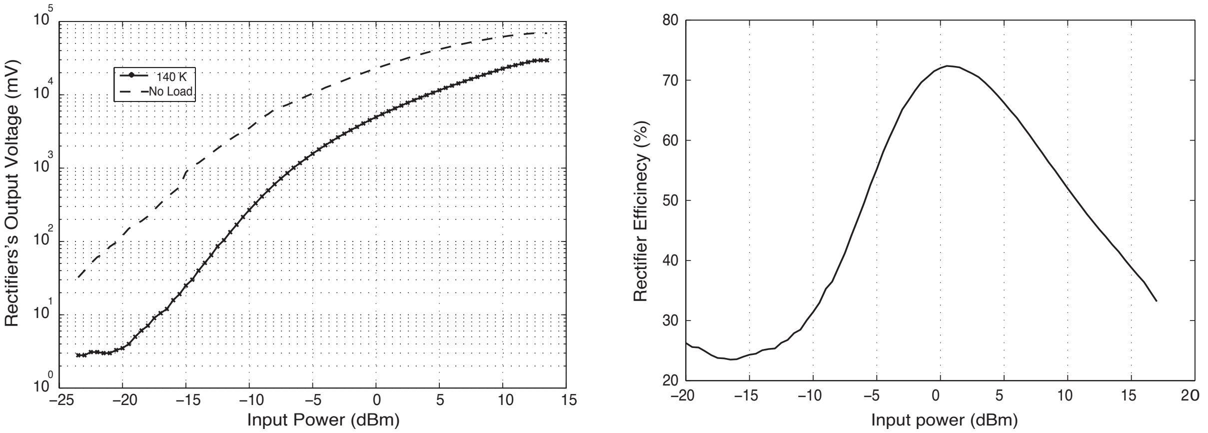
The preliminary results of the project were published in [38]. Our plan to further optimize the design of the iPoint is as follows:

- *Size:* The latest version of the prototype, Version 2.1, consists of two separate PCBs. We attempt to decrease the physical size of the device by unifying the old boards in the future versions of the prototype.
- *Antenna and matching:* In order to further miniaturized the device, we plan to replace the whip antenna in the old design with a compact integrated (PCB) antenna. The new design features a new matching circuit that is significantly easier to tune.
- *Simulations:* we plan to perform an extensive set of simulations using Agilents ADS simulation package in order to choose the optimal values for electronic components of the design. Simulation validation will also help to predict the performance of the new designs before printing new PCBs and results in reducing the project cost.

4 Energy and Information Transfer in Bio-enabled Wireless Networks

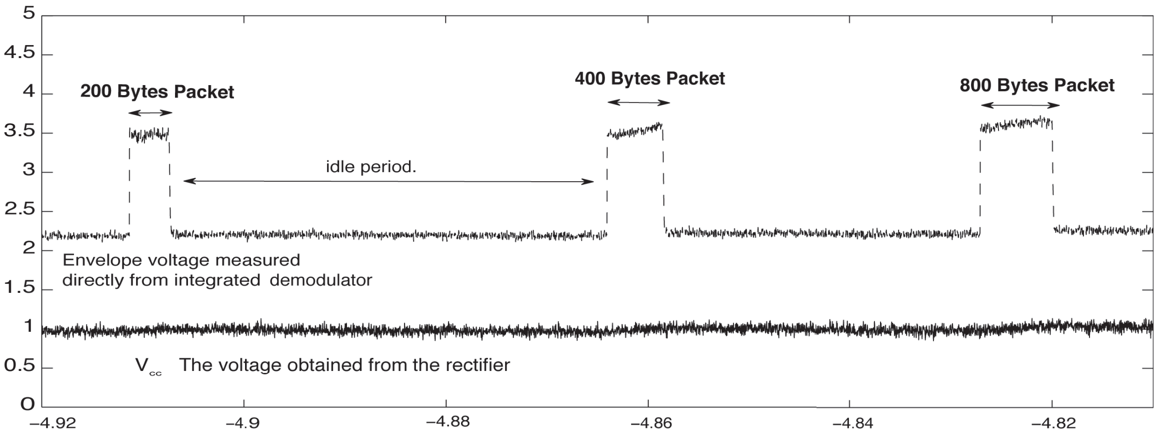
While energy efficiency remains one of the main challenges in wireless networks [1, 2], biological systems are well known to be extremely energy efficient. From the brain, which performs outstandingly complex tasks with only a few tens of Watts, to the ear, which can carry out the equivalent of a billion floating-point operations per second, biological systems are many orders of magnitude more efficient than our state of the art wireless systems. Such an efficiency gap can be explained by the fact that today's electronic systems rely on transistors (∼30nm) to perform very basic functions, while biological systems rely on nano-level machines (e.g., proteins) to perform specialized and complex functions. A natural, although clearly challenging question is if we can build biologically-enabled wireless networks. Note that the theme of this research is bio-enabled mechanisms which are fundamentally different from bio-inspired techniques in which the functionality of the electronic device is inspired by an existing natural mechanism. This quantum leap in efficiency is analogous to the improvements from Pascal's mechanical calculators to electronic calculators. We argue that recent advances in bio-engineering technology and synthetic-biology will dramatically expand the frontier of wireless communication research.

An example of systems that can benefit from such research is a wireless sensor network. Most wireless sensor nodes rely on a periodic wakeup to be paged for requests. This results in significant energy consumption and increased delay. A Bio-enabled Sensor Network (BSN) composed of a nano-power sensing device that can go into a full sleep mode but can still be woken up using a fairly long-range RF signal could solve this problem. The idea is to transduce a weak Electro-Magnetic

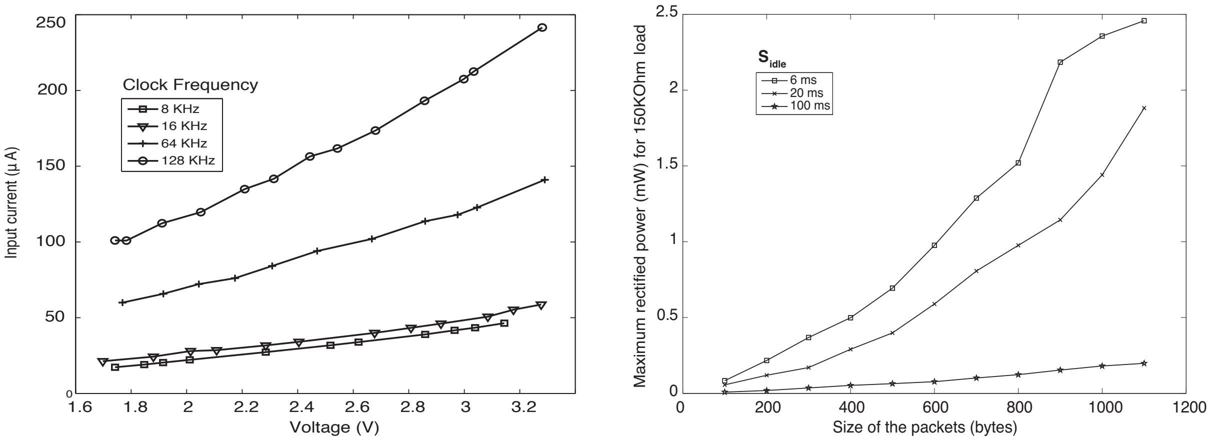


(a) Performance of the energy harvester unit.

(b) Energy-harvester efficiency as a function of input power.



(c) The outputs of Energy harvester (V_{cc} and integrated demodulator (envelope signal). Note that the size of the packet is easily detectable. The WiFi communication rate was fixed to 1 Mbps. harvester's output level is fairly smaller than the peaks of envelope signal. That reason is the long idle times between packet transmissions. The data is captured by a Infinium MSO8104 oscilloscope from Agilent Technologies. The plot is regenerated in MATLAB.



(d) Power consumption of MCU for different clock frequencies.

(e) The rectified output voltage as a function of the packet length for different idle times S_{idle} (therefore duty cycles).

Figure 7: Performance evaluation results.

(EM) signal into biological signals and use a biological device to demodulate the information embedded in the original EM signal [34].

A second application is the engineering of bio-agents that can synthesize and self-assemble a protein/polymer-based radio receiver (such as the recently demonstrated nano-radio [39]), that diffuses through the body and targets specific cells such as cancerous cells, liver cells, or even neurons (by generating anti-bodies that binds to targeted membrane proteins [20, 40]) to allow the remote monitoring, manipulation (e.g., opening/closing ion channels as demonstrated in the remote control of C. Elegans worms [24]), and even destruction (e.g, by triggering apoptosis processes) of the targeted cells.

An exciting challenge at the frontier of three research communities, namely communication networks, bio-physics, and synthetic biology, is how we can design a wireless communication system that:

- *Interfaces* with bio-organisms for medical applications such as remote control, and monitoring of cells.
- *Leverages* bio-computation and communication for efficiency.

Building bio-enabled wireless communication systems requires overcoming several challenges.

- *Signal propagation:* is challenging because bio-materials severely limit the propagation of wireless signals (e.g., electrical fields are highly attenuated) [41].
- *Interfacing:* controlling bio-physical processes is difficult as these processes are still not well understood, and sensing and extracting bio-signals to the external world is not easy using non-invasive self-assembling devices.
- *Size:* devices should be small enough to interface with bio-mechansims at the molecular level.
- *Robustness and stability:* bio-organisms are very sensitive to the environment and need to be engineered for extreme environments[36].
- *Health:* the proposed technology should be safe to people and the environment.

4.1 Basic Concepts

Connecting two seemingly different worlds requires detailed understanding of their similarities and differences. While biological organisms seem to completely differ from electronic circuits used to built wireless networks, a closer look at these complex systems reveals a few fundamental similarities. This section presents an overview of the biological world from systems perspective and breaks down some of its important characteristics:

Information flow and biological sensitivity In systems biology, an organism can be viewed as a complex network of its cells. A cell is a well-defined biological entity able to receive (sense), process, and generate information. In this biological network, information travels using *bio-signals*. Bio-signals exist in the form of mechanical, chemical, or in some cases electrical signals. Examples include pressure, signaling molecules such as hormones, ion concentration change, and electrical pulses produced in neurons. From systems perspective, there are three types of bio-signals.

- *External stimuli:* the information perceived by the cell from the extracellular micro-environment. These signals activate a specific receptor (i.e. a protein located on the cell membrane) on the cell and trigger a reaction.
- *Intracellular signals:* intermediate signals produced inside the cell in the process of creating the response. These steps normally include numerous chemical reactions and protein-protein interactions.
- *Cell responses:* the output generated by the cell, which alters the state of the cell or the extracellular environment.

The process by which a cell generates a response to an external stimuli is called *signal transduction*, and the sequence of steps required to complete the process is referred to as *signaling pathway* [42]. The correct execution of the transduction relies on availability of necessary proteins in the cell. Cells produce such proteins using information encoded in their genetic code. The biological behavior of the cell in an environment depends on the variety of its signaling pathways. In multi-cellular organisms, the complex network of signaling pathways coordinates the function of the organism as a whole. Understanding the information flow in signaling pathways allows the use of a bio-organism as a tool for computation and communication. In addition, advanced *synthetic biology* and *genetic engineering* techniques have made it possible to design and engineer new signaling pathways with enhanced functionality [35]. The sensitivity of a cell to external stimuli is determined by the variety of its receptors, special proteins that normally reside on the cell membrane. Receptors are classified by the stimuli to which they are sensitive, as well as the signaling pathway they trigger. External stimuli include temperature change, mechanical stress and strain, signaling molecules, or a change in electrochemical voltage in the environment.

Speed Signal transduction execution time depends on the complexity of the pathway and varies for different cell responses. A change in sodium ion concentration in neurons completes in a few milliseconds while a complicated process such as gene expression might take days to finish [42].

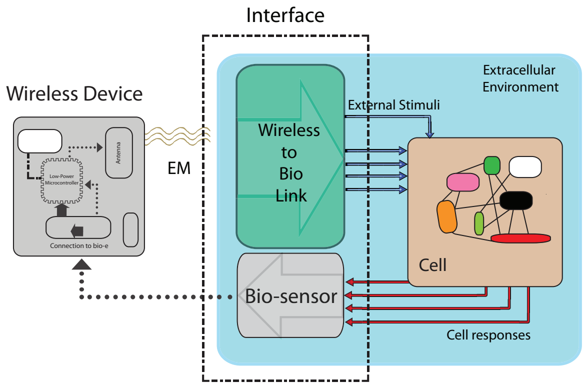


Figure 8: The components of a simple interface between a cell and a wireless device.

Energy Natural selection has forced bio-organisms to maximize their energy efficiency. Biological organisms show superior energy efficiency compared to today's ultra-low power electronics. As an illustrative example, human brain consumes 20–30 watts of power, less than a third of most advanced CPU designs [43]. Also, ears and eyes outperform the state-of-the-art sensors at the same level of energy consumption.

Complexity Even in the simplest form (i.e. single-cell), bio-organisms manage to perform a variety of complicated tasks. The ability to produce a vast number of proteins with different functionalities permits bio-organisms to extend the complexity of their actions while preserving their size and efficiency.

4.2 Approach

In a biological system, each cell can be modelled as a Multiple Input Multiple Output (MIMO) device where inputs and outputs denote external stimuli and cell responses, respectively. On the wireless side, a wireless node exchanges the information with its surroundings using high-frequency electromagnetic (EM) signals. Depending on the communication scheme, information is encoded in amplitude (energy level) or the frequency of the signal. An interface should provide an efficient channel to exchange *information* and *energy*. It should not perturb the functionality of either side, which is particularly important for the biological entities because of their high sensitivity to environmental changes. Ideally, the interface does not concern how information is processed at its endpoints such as details of decoding schemes in the wireless node or the internal signaling pathway in cells. In our model, the endpoints of the interface are assumed to process the information and generate signals without error.

Figure 8 illustrates a simple two-way interface between a wireless node and a cell. The information flow consists of the following two links:

- *Cell to node:* Cell responses normally alter the state of the surrounding micro-environment. Therefore, a wireless node equipped with a properly designed *bio-sensor* can observe the effect of a cell response in the extracellular environment in a non-invasive fashion. Bio-sensing techniques used to extract the information from bio-signals are beyond the scope of this work, but an extensive body of multidisciplinary research can be found in the literature for interested readers [44, 45].
- *Node to cell:* To trigger any cell response, the corresponding combination of stimuli should be present. Either propagation of EM signals directly produces a stimulation in the extracellular space, triggering a transduction process, or the cell perceives a secondary effect of the EM signal delivered by auxiliary nano-devices. The possibilities and challenges to create the link from wireless device to biological system are the main focus of this part of our research and discussed in detail in the following sections.

The main goal of interfacing mechanism is to convert the message sent by the wireless node in the form of an EM signal to a meaningful set of bio-signals. At the molecular level, EM signals can be seen as series of changes of EM fields in the environment.

Systematic noise Biological systems, similar to any communication system, experience systematic noise [46]. Since interactions and signaling in biological systems happen at the molecular level, the energy level of the contributing particles (molecule) nears $k_B T$; hence, the system contains a substantial amount of thermal noise. To ensure a successful activation of the receptor, the energy level of the transduced bio-signals must exceed the threshold level of one or two order of magnitude greater than the system's thermal noise. The high volume of the noise in the system makes efficient signaling quite challenging.

4.2.1 Signal Transduction

One approach to signal conversion is to use the immediate effect of the wireless signal (i.e. meaningful changes in electric and magnetic fields) as the biological stimulus. Some cell receptors are known to be sensitive to electrochemical voltage variations. For example, ion channels are trans-membrane proteins that control the concentration of a specific ion across the cell membrane by regulating the ion flux. Meaningful changes in an ion concentration such as calcium (Ca^{++}) have been shown to trigger several signaling pathways, and serve as the key mechanism involved in the inter-cellular signaling [33]. For example, the voltage-gated ion channel, which is activated by electrochemical voltage variation, is potentially suitable for interaction with EM signals. The direct use of EM signals as biological stimulation meets the following pair of challenges:

- *Electrical attenuation:* The extracellular fluid is electrically conductive due to the concentration of ions and polar molecules. Therefore, the electric field becomes largely attenuated while propagating in the biological environment [41]. In other words, electrical properties of the biological environment channel the energy of the signal to particles other than the target molecule. This forms a two-fold obstacle: reducing the energy of the transduced signal below the detection threshold, as well as creating the possibility of unintended activations elsewhere.
- *Magnetic blindness:* Research has shown that biological systems exhibit limited interactions with magnetic fields due to the absence of magnetic materials [46]. Although natural magnetoreception has been spotted in rare organisms such as magnetotactic bacteria and the migratory birds [47], most biological systems lack the natural ability to perceive the magnetic field. However, it is possible to synthetically add a magnetic receptor to the cell. See section 4.3.1 for more details.

A limited number of cell receptors are able to perceive EM fields. In fact, most of the signaling pathways are regulated by chemical, thermal or mechanical stimulation. A more practical approach is to construct a non-EM biological stimulus from the secondary effects of EM signals in biological media. A few possibilities are listed below:

- *Thermal:* It has been shown that high frequency EM fields generate heat while propagating in biological media. Given sufficient amount of time, it may create a temperature increase competent to activate a targeted thermoreceptor [48].
- *Mechanical:* Electric and magnetic fields produce mechanical effects (i.e. Force, Torque, etc.) on charged and magnetic materials. Such effects generate a series of motion, vibration, stress, or strain in the cell structure that can be detected by a mechano-sensitive receptor that resides on the cell membrane [49].
- *Chemical:* A combination of thermal and mechanical interactions can be used to release an originally trapped signaling molecule in the extracellular environment, consequently causing the activation of corresponding receptor [24].

4.3 Enabling Technologies

Efficient and effective implementation of the mechanism mentioned above often requires auxiliary machinery. These nano-scale machines (structures), or simply *bio-devices*, provide the required functionality and compatibility to facilitate the signal conversion in the biological environment. Due to the small size, they can safely attach to biological surfaces or float in the extracellular environment. In this section, we discuss potential enabling technologies that can be integrated, or possibly combined in the design of an efficient and robust interfacing mechanism. The current state of the technology, challenges, and the improvement possibilities are summarized.

4.3.1 Mechanical Nanoresonators Coupled with Electromagnetic Fields

Mechanical nanoresonators exhibit resonance behaviour involving the mechanical vibrations of the system elements. The natural frequencies of such resonances will, generally, be in the radio frequency range. Nano-scale mechanical resonators coupled with electromagnetic fields have been receiving significant attention recently [39, 50, 51]. The ability to interact with electromagnetic fields allow such resonators to be essential parts of nano-scale systems. Imaging, sensing, and targeted actuation in nano scale are among several emerging technologies that rely on efficient energy and information transfer.

In principle, nanoresonators may couple to electromagnetic fields by the charge distributions (Electric coupling) or by the magnetic moment they carry (Magnetic coupling). Traditionally, electric coupling has received more attention since the electric field intensity is much larger than magnetic field intensity in electromagnetic waves. On the other hand, magnetic coupling of mechanical resonators with electromagnetic waves becomes more practical as the size of the system decreases. In

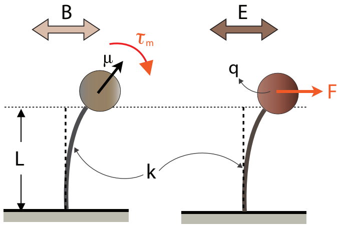


Figure 9: An overview of nanoresonators with electric (right) and magnetic (left) coupling. The viscoelastic properties of the resonators are identical.

fact, magnetic coupling holds important advantages over electric coupling. First, magnetically coupled systems can provide more *selective* and *localized* energy transfer. That is due to the fact that magnetic fields, unlike electric fields, couple weakly with non-targeted surrounding media, which are often not magnetic. Therefore, magnetic signals penetrate deep in various kinds of media, suffer from considerably less attenuations, and interact with targeted resonator inaccessible to electric signals with the same level of energy. In addition, magnetic dipoles are normally more stable than electric dipoles, and do not require significant energy from outside to maintain their state.

We propose to investigate the interactions of radio-frequency electromagnetic fields with mechanical nanoresonators, particularly quantitative assessment of the energy transfer in such nanoresonators. First, we present a universal model for mechanical nanoresonators that includes electric and magnetic coupling, and describe the dynamics of the system.

Theoretical Model Here, the mechanical structure of the nanoresonator consists of an elastic cantilever beam equipped with a specialized tip, which is responsible for electromagnetic interaction, vibrating in a low-viscosity fluid such as low-pressure air. The viscoelastic model of the nanoresonator includes the coefficient of mechanical elasticity, k, and the dissipation coefficient, D. For a cylindrical beam with a spherical tip, $k \sim EI_\mathrm{c}/L^3$, where E, I_c and L are Young's modulus, second moment of cross-section and the length of the beam, respectively. Moreover, as shown in Ref. [52], the combination of intrinsic (e.g., plastic deformation, surface effects) and extrinsic (e.g., viscous forces of the surrounding fluid) dissipation mechanisms determines the value of D. Because the size of the nanoresonator is much smaller than the wavelength of the external field, the energy transfer is in the form of interactions between the incoming field and dipole moment of the nanoresonator's tip. In this work, we look at two nanoresonators that have identical mechanical structures, yet interact with electromagnetic fields via different coupling mechanisms: Electric coupling $(\mathfrak{E})$ and *Magnetic coupling* $(\mathfrak{M})$. In electric coupling, an AC electric field, $E = E\cos(\omega t)$, produces a force, F, on an electric charge distribution, q, placed at the tip of the nanoresonator and causes oscillatory deflections in the cantilever. A very similar model has been discussed in the *Nanotube Radio* [39]. For magnetic coupling, assume the tip of the resonator is made of a ferromagnetic material such as magnetite (Fe_3O_4) and has a magnetic moment of μ. An AC magnetic field, $B = B\cos(\omega t)$, generates a magnetic torque, $\mathcal{T}_\mathrm{m} = \mu \times B$, and rotates the tip leading to oscillatory beam deflections. A device based on this model has been built and used for *ultra-sensitive magnetic resonance force microscopy (MRFM)* [50, 53]. Figure 9 illustrates the mechanical structure of the nanoresonator and the aforementioned coupling mechanisms. We begin by looking at the dynamics of each model, then look closely at the resonant energy transfer performance of the nanoresonators.

The dynamics of the system can be expressed by Langevin motion equation for the tip of the resonator. After linearization for small deflections, we have

$$m_\mathrm{f}\ddot{x} + D\dot{x} + kx = F\cos(\omega t) + N(\omega t), \tag{5}$$

where x is the displacement at the tip of the beam, m_f is the effective mass of the system, and D is the dissipation coefficient. $F = qE$ for electric coupling, while $F = \mathcal{T}/L = \mu B/L$ for magnetic coupling. The term $N(\omega t)$ is an stochastic force with the correlation of $\langle N(t)N(t+\Delta t)\rangle = 2Dk_\mathrm{B}T\delta(\Delta t)$, where k_B and T are the Boltzmann constant and temperature in Kelvin, respectively. In our systems of interest, as will be shown later, the amount of energy stored in the resonator is well above $k_\mathrm{B}T$. Therefore, we safely omit the stochastic term from (5). The system's natural frequency and the quality factor are given by

$$\omega_0 = \sqrt{\frac{k}{m}} \tag{6}$$

$$Q = \frac{\sqrt{km}}{D}. \tag{7}$$

The steady state solution of the system is

$$x(\omega t) = x_\mathrm{m}\cos(\omega t + \varphi), \tag{8}$$

where x_m and φ are the maximum deflection of the tip and the phase shift given by

$$x_\mathrm{m}(\omega) = \frac{F/m}{\sqrt{(\omega^2 - \omega_0^2)^2 - (\omega\omega_0/Q)^2}} \tag{9}$$

$$\varphi(\omega) = \arctan\left(\frac{\omega\omega_0/Q}{\omega^2 - \omega_0^2}\right). \tag{10}$$

Finally, the necessary condition to achieve resonance is $D < \sqrt{2km}$.

The dynamics of the system can also be expressed by the following Langevin equation for rotational oscillation.

$$I\ddot{\theta} + C\dot{\theta} + \kappa\theta = \mathcal{T}\cos(\omega t) + \psi(\omega t) \tag{11}$$

Here $\theta = x/L$ is the angular displacement, $I \sim mL^2$ is the system's second moment of inertia, $\kappa \sim kL^2$ is the rotational spring constant of the cantilever, and ψ is the stochastic torque caused by the thermal noise. For magnetic coupling, $\mathcal{T} = \mu B$, while $\mathcal{T} = qEL$ in the case of electric coupling. The natural frequency, quality factor, the steady state solution, and resonance condition will be identical to the previous approach. A detailed analysis can be found in our previous work [56].

4.3.2 Non-radiative energy transfer mechanisms

Electromagnetic radiation dilemma During Electro-Magnetic Radiation (EMR), energy is transmitted as electro-magnetic waves. For a plane wave of a fixed frequency, the power density of the wave is given by its *poynting vector*,

$$\mathrm{S} = \frac{1}{\mu_0}\mathrm{E} \times \mathrm{B} \tag{12}$$

Also, the time-averaged magnitude of the poynting vector is

$$\langle S \rangle = \frac{{E_0}^2}{2\mu_0 c} \ \ \mathrm{W/m^2} \tag{13}$$

Where E_0 and c are maximum amplitude of the electric field and speed of light, respectively. Accordingly, the maximum amplitude of the electric and magnetic fields at distance R from an omnidirectional antenna transmitting at P watts is,

$$E_0 = \sqrt{\frac{\mu_0 c P}{2\pi R^2}} = \sqrt{\frac{60P}{R^2}} \qquad B_0 = \frac{E_0}{c} = \frac{\sqrt{60P}}{Rc} \tag{14}$$

Therefore, at the distance of 10 cm, a 1W wireless transmitter generates a surprisingly small magnetic field of intensity $B = 2.58 \times 10^{-7} \approx 0.26\ \mu$T, which is almost 100 times weaker than average geomagnetic field, 30 to 60 μT. The effect of such a small field on nano-scale magnetic particles is infinitesimal. This critically challenges the feasibility of signal conversion from electromagnetic waves (i.e. radiative EM signals). In contrast, an energy transfer based on electrodynamic induction requires strong alternating magnetic field can be generated simply by physically rotating, or feeding an alternating current (AC) to an electromagnet. In this case, the interaction of magnetic particles and the field is not radiative, and the energy transfer falls in *near-field* category [54].

Moreover, new techniques for solar energy conversion, inspired by photosynthesis in leaves, use non-radiative dipole-dipole coupling for direct transfer of energy also called Forster resonance energy transfer (FRET). These near-field interactions, first discovered by Jean Baptiste Perrin, allow an excited donor molecule to transfer the excitation energy through direct electrodynamic interaction at resonance without the emission of a real photon (i.e. radiation). Perrin's model predicted that energy transfer could occur over distances of up to the visible spectrum wave length (~500 nm), yet later discoveries by Forster showed the distance must be reduced by factor of 100 because of imperfections in the resonance. A similar principle applied to radio waves provides efficient wireless non-radiative energy transfer. WiTricity [19, 55], based on resonant inducting coupling, demonstrates the transfer of high amount of energy (~ 60 W) over a distance of 2m at remarkably high efficiency (~40%). Although the size of the implemented system (coils of radius 40 cm) is a great deal larger than MNP dimensions, the theoretical analysis supports the possibility of similar resonant coupling in nano-scale [55]. It is possible to couple an external resonator to an engineered nanocoil attached to a targeted receptor, creating an exclusive and efficient channel of energy from outside to the biological system.

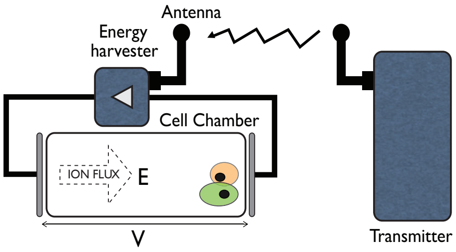


Figure 10: Signal conversion using Energy harvester.

4.3.3 RF Energy harvesting

Normally, due to limited resources, the transmitted signals from wireless devices contain little amount of energy. This is not the optimal scenario considering that the efficiency of the signal conversion at a passive interface, regardless of signal types, is proportional to the energy level of the incoming signal. A wireless energy harvester unit similar to one that was described in section 3.3 can be used to accumulate the energy of received EM signals over time and provide a high-energy signal, which can be converted to the desired bio-signal through a simpler and more efficient process.

4.4 Future Work Plan

We propose the following steps to complete the research:

- *Electromagnetically Coupled Mechanical Nanoresonators:* We perform energy transfer analysis for the presented theoretical model. Using *coupled-mode theory*, we determine the performance of energy and information transfer for mechanical nanoresonators with different types of coupling. Our preliminary results first appeared in [56]. Also a more advanced analysis is currently under review for publication [57].
- *Energy Harvesting Assisted Transduction:* We plan to investigate use of energy harvesting as an intermediate auxiliary step to transduce electromagnetic energy to biochemical signals. Figure 10 shows a possible configuration. We look into possible methods to create an efficient identification (Address recognition) scheme for wireless-bio interfaces, and determine their performances analytically. Our preliminary results has been published in [34]. We plan to model the address recognition in a suitable finite-element simulator to validate the results. At the end, if time permits we consider to build a prototype of the device using microfluidic fabrications and evaluate the performance experimentally.

5 Schedule

The following table is the proposed timeline to complete the research:

To-do tasks	Completion Date
Proposal Defense	May-June 2012
Energy transfer performance analysis for mechancial nanoresonators	June 2012
iPoint unified design with the integrated antenna	June-July 2012
Address recognition scheme modeling and analysis	July-August 2012
Ph.D. Dissertation Defense	September 2012

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