Towards Ubiquitous IoT through Long Range Wireless Energy Harvesting

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ABSTRACT

Extending the range of RF energy harvesting can revolutionize battery-free/low-power sensing and networking. This paper explores the design space for RF infrastructure to charge battery-free devices (e.g. RFID) or devices with coin-cell batteries (e.g. water and security sensors) over much longer range than the state-of-the-art. Rather than rely completely on ambient RF (e.g. TV towers) or dedicated infrastructure (e.g. RFID readers), we explore a middle path – combine RF energy from (nearly) all available major wireless frequency bands and then supplement this with low-cost specially designed RF charging infrastructure to fill in any gaps.

We propose SCALED, an architecture that extends the energy-harvesting range of ultra-low-power platforms. We explore two design questions: (1) The design of the energy harvester, including which ambient frequency bands to combine as well as overall modalities to combine energy rather than focus on one band; (2) The design of radio infrastructure to fill-in the coverage gaps of ambient energy, with minimal interference to communication sources. We implement and study SCALED through a multi-pronged evaluation including building-scale proof-of-concept deployments.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing systems and tools**; • **Networks** → *Network range.*

KEYWORDS

RF Energy Harvesting; Ubiquitous IoT; Long Range Harvesting

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1 INTRODUCTION

In this paper, we ask – "Can we scale the ubiquity of ultra-low power wireless energy harvesting IoT devices without increasing the density of their RF energy sources?". Achieving such a goal require extending the current range of energy-harvesting to wirelessly power such IoT devices. Indeed, long-range wireless power could enable, say, backscatter or energy-harvesting-based sensing platforms to operate reliably – outdoors or indoors. This could enable applications ranging from inventory monitoring, package tracking, basement water sensing, animal health sensing, etc. These applications require sensing and communication platforms that are inexpensive, mobile and capable of running on harvested energy. Uniquely, unlike say solar or other power sources, wireless energy could enable power harvesting indoors and outdoors all times of the day and within enclosed spaces (e.g., tracking location or sensing tamper of packages through the mail system).

There has been much prior work on ultra-low-power platforms, with billions of passive RFIDs (Radio Frequency Identifiers) forming the biggest chunk. Current passive RFID platforms have a limited range of tens of meters, requiring readers in close proximity. For example, although RFID technology is widely deployed in today's warehouses and airports, inventory scan requires either deploying a reader every 15 m, or an employee walks around while carrying an RFID reader. This range can be extended to tens of meters using drones working as RF relays [32], altering tag hardware design [25], using directional antennas [17], or designing blind beamforming using distributed and synchronized readers [52]. More recently, ambient energy-harvesting proposes not relying on dedicated readers whatsoever, and instead to harvest energy from ambient sources such as TV towers, LoRA base stations or Wi-Fi access points [13, 26, 27, 30, 38, 50]. A third body of work on wireless power transfer [14, 23] seeks dedicated high-power infrastructure for energizing wireless nodes rather than including and co-existing with available ambient energy from radio towers. These diverse approaches beg the question – *Is an additional energy-harvesting infrastructure even necessary, if existing RF communication sources, e.g., TV towers, already exist?* And even if such infrastructure is needed, what would be the minimal additional RF sources needed to blanket a desired space with sufficient RF energy for ultra-low-power IoT to provide ubiquitous and (near-)reliable access to power?

This paper presents SCALED[1], an architecture that explores the key design decisions to deliver sufficient RF energy for ultra-low-power devices (e.g. RFID and coin-cell powered sensors) over longer range than the state-of-the-art. Our contributions are two-fold: (1) A design space exploration for the RF energy harvester that spans multiple, wide RF frequency bands; (2) The design of minimal supplementary radio infrastructure that fills-in-the gaps in wireless energy coverage without posing significant interference to RF communication incumbents. Across the board, we implement and evaluate designs of SCALED.

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[1] Supplementary Charging Architecture for Low Energy Devices

Energy Harvester System Design: SCALED's core design principle is to leverage as much pre-existing ambient energy as possible and supplement this with additional wireless infrastructure to achieve desired levels of coverage, only as a last resort. This leads us to a natural implication for the design of our energy harvester – rather than harvesting at any one dedicated frequency band, why not combine RF energy across bands? In other words, SCALED seeks to harvest the combined total energy of ambient as well as dedicated RF energy sources *across several frequency bands*. As harvesting RF energy is frequency agnostic, and in principle transmitted energy over multiple frequencies should add up without the need for aligning phases in standard beamforming [52]. While, there are existing circuit designs in the research community for multi-band RF energy harvesting [34, 37, 39], their evaluation is primarily through simulation and bench-top tests. Thus, there is a lack of system design exploration and experimentation to evaluate multi-band harvesting in the wild. To this end, we explore the design space of the energy harvester – that straddles the TV frequencies, cellular and WiFi, including precise modalities of combining energy and the overall choice of frequency bands.

Radio Infrastructure System Design: Further, we address designing SCALED's energy source platform to best complement ambient energy over long range. Specifically, we consider two key questions. First, we orchestrate our energy sources to effectively power tags over long range and avoid interference with other devices. To this end, and in the absence of ambient communication, each source politely accesses the medium by adding extra delay before transmitting an excitation signal with periodic gaps. These extra delays and gaps prevent existing band incumbents such as WiFi device from endlessly backing off and allow frequent windows to gain access to the medium. However, in the presence of pre-existing ambient RF, each source behaves like a repeater rather than an interferer, thereby in fact having the virtuous side-effect of improving signal throughput or coverage of the communication radio. Second, we address the crucial design parameter of transmit frequency that determines how much energy the low-power device harvests, and thus is key to minimizing the total infrastructure needed to cover a space. Our experiments show that owing to signal multipath, at any given location of a SCALED's energy source and the harvesting device, the choice of frequency can play a pivotal role in how much energy the device harvests – often making a difference between the harvester operation and power failure. To tackle this, we design a solution that probes an extremely small set of frequencies to model radio waves propagation approximately and predict the most rewarding frequencies that maximize the total harvested energy.

We implement and evaluate SCALED on software defined radios (USRPs) and commodity WiFi radios, while supplying RF energy at three bands: TV whitespaces (vacant radio spectrum in TV broadcast bands) at 470-698 MHz, 902-928 MHz, and 2.4-2.5 GHz ISM band. We develop a custom battery-less energy harvesting platform in collaboration with an energy harvesting collaborator (Powercast [6]) to harvest energy from multiple bands. Our results show:

- Harvesting 29.5 μW RF energy at a range of 130 m indoor, and 10.9 μW at a range of 419.1 m outdoors.
- A net power harvested improvement of 28.5 μW vs. harvesting from multiband ambient harvesting (with 1.2 μW).
- A 52% improvement in harvested energy over randomly selecting an excitation frequency.
- Insignificant impact on traditional WiFi communication in terms of throughput, and packet loss.

Contributions: We explore wireless energy harvesting infrastructure that can supplement ambient energy, extend its range and coexist with ambient communication for battery-free IoT devices along two axes: (1) A multi-band RF energy-harvester (see Sec. 3); (2) Radio infrastructure that supplements ambient wireless power to fill in the gaps and extend the energy coverage in a non-interfering manner (see Sec. 4). The system is implemented (see Sec. 5) and evaluated through a detailed multi-pronged study (see Sec. 6).

2 OVERVIEW OF SCALED

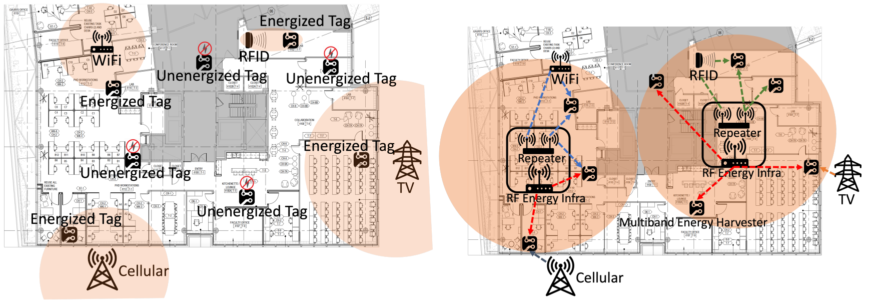
This section provides a brief overview of SCALED. SCALED primarily targets extending the range of energy coverage for ultra-low-power IoT devices. Therefore, the design of SCALED is primarily motivated by two important objective functions: 1) maximizing the coverage of energy harvesting by extending its range and 2) ensuring minimal disruption to existing communication infrastructure.

Fig. 1 illustrates the coverage improvement of SCALED over existing RF energy harvesting systems. SCALED contains two components as shown in Fig. 1(b): *RF Energy Infrastructure* and a *Multi-band Energy Harvester.* The energy source operates in the absence of ambient radios to maximize RF energy harvested at the device. Should an ambient communication transmitter begin to transmit, the energy source backs-off and the repeater amplifies this transmission to ensure that a distant energy-harvesting device receives sufficient and reliable energy, without disrupting communication.

The rest of this paper describes the two key components of SCALED's design: 1) How we design a multiband yet efficient energy harvester? 2) How we design this RF energy infrastructure that can extend the range of energy harvesting while coexisting with ambient communication signals?

Multiband Energy Harvester: We design a multiband RF energy harvester that can add up energy from six frequency bands that we choose carefully to maximize ambient harvested energy while regulations permit our infrastructure to supplement such ambient energy. Further, we co-design the energy harvester and the radio infrastructure to keep each of the six bands always energized.

Radio Energy Infrastructure: Feeding RF energy to distant IoT devices, requires careful control of energy transmission to maximize harvested energy while avoiding interference with ongoing wireless communication. The co-existence module in our energy source starts by sensing a given frequency using carrier sensing. If the channel is vacant, our energy source avoids collisions by using a more "polite" version of carrier sense vs. standard WiFi – i.e., waiting for an extra random delay over the standard interframe spacing. It then begins to transmit an excitation signal on the frequency selected previously. Even if the channel is busy, SCALED uses its repeater to amplify the received signals and transmit them back to ensure continued and long-range energy harvesting. This is important since ambient wireless signals are often too feeble to sufficiently power RF tags (see Sec. 4.1 for more details). Another component of SCALED answers the question "What are the most rewarding frequencies in terms of harvested energy?". Given



(a) Current RF Energy Scattered Coverage.

(b) SCALED's coverage.

Figure 1: Coverage of current RF energy harvesting versus SCALED's coverage. SCALED combines the best of ambient and dedicated (e.g., RFID) energy harvesting. While existing RF energy harvesting has limited range (a), SCALED extends that range by two steps: 1) accumulating energy over multiple bands; 2) supplementing ambient energy with excitation signals at ISM bands and TV whitespaces.

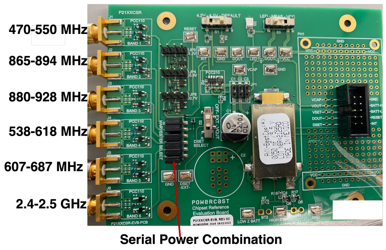


Figure 2: Custom designed multiband energy harvesting board that serially combines harvested power from carefully chosen 6 bands. These bands target either widely deployed RF infrastructure or bands in which the transmission of excitation signal is allowed.

that RF energy harvesting systems are more prominent in indoor environments, where multipath fading has significant effects, the most rewarding frequencies are not necessarily the ones with the lowest path loss. Therefore, we design an algorithm (in Sec. 4.2) that creates an approximate radio propagation model by probing a tiny set of frequencies. Using this, we predict the frequencies that maximize the harvested energy, and hence extend harvesting range.

3 MULTIBAND ENERGY HARVESTER

Developing a multiband energy harvester to efficiently add up energy from different bands entails multiple design decisions such as the choice of either a single wideband antenna or multiple tuned antennas; multiple tuned rectifiers, filters and matching circuits.

Choice of Frequency Bands. To achieve our vision of wide-area coverage of energy harvesting, we specifically target congested RF bands with widely deployed technologies and hence have wide coverage. These RF bands include TV 470-690 MHz bands, the cellular 865-894 MHz downlink band, 880-928 MHz, and 2.4 GHz. We choose the TV bands to leverage ambient TV signals, widely deployed for TV over-the-air channels. Moreover, SCALED energy infrastructure can utilize the wide available bandwidth of TV whitespaces to supplement ambient TV energy. SCALED complies with TV whitespaces regulations by checking the whitespace databases every day to use the vacant frequencies. Further, we add up energy from the cellular 865–894 MHz downlink band as well, as cellular has a 95% worldwide population coverage [2]. We focus on a downlink band as it offers SCALED relatively more energy (when compared to the uplink), with the exact quantum depending on the coverage of nearby cell towers [34]. Among these six bands, we use U.S. ISM band part from 902–928 MHz, in which we can harvest energy from multiple technologies including LoRa gateways, RFID readers and ZigBee transponders. The radio energy infrastructure of SCALED can also supplement ambient energy by transmitting signals at this ISM band. Similarly, at 2.4 GHz, we can add up energy from several technologies such as WiFi, Bluetooth, cordless phones, microwave ovens, as well as supplement energy using our infrastructure.

Here, there is a trade-off in circuit design between the circuit complexity and efficiency of energy harvesting. For example, using a single multiband antenna can simplify and minimize the size of the harvester, but on the other hand it may not efficiently receive signals over wideband of frequencies starting from 470 MHz up to 2.5 GHz. Given these bands are not nearby, it is inefficient to leverage a single wideband antenna. Therefore, we leverage a tuned antenna per harvesting band to maximize harvested energy. Similarly, to minimize reflected energy (S11), a separate matching circuit and bandpass filter is tuned for each frequency band and the received AC current is fed to a high-efficiency RF-DC converter chip (PCC110 [6]) with a wide frequency range (10MHz to 6GHz). This chip rectifies the AC current using a diode rectifier circuit.

Power Summation. Combining harvested energy from these different tuned harvesting circuits is non-trivial. When one band is not energized, their diodes (rectifiers) switch from a voltage source to a voltage drop, impacting the current flowing from the energized bands [37, 39]. SCALED approaches this challenge by co-designing the energy harvester and the RF energy infrastructure to maximize the harvested energy. Although, a serial combination of the energy harvesters is inefficient if one of the bands is not excited, it can harvest maximum energy if all bands are excited. Thus, SCALED's energy infrastructure makes sure that all bands at each energy harvester are energized by supplementing the available ambient signals with enough RF energy. After converting the current harvested from AC to DC at each band, we add up these currents by connecting them serially. Accumulated energy can then be measured as either a current source or a voltage source. It is important to note that SCALED keeps monitoring levels of harvested ambient energy and feeds enough energy to supplement unexcited bands as needed, except the licensed cellular downlink band. While cellular has extensive coverage [2], we observe nearly continuous non-zero ambient harvested energy that prevents switching such a link from energy source to a voltage drop. Moreover, the cellular downlink band tuned circuit (865–894 MHz) is not far and actually overlaps with the ISM band tuned circuit (880-928 MHz) which results in harvesting energy by the cellular band circuit either from ambient ISM band sources or from our energy infrastructure.

Hardware Specifications. Through collaboration with Powercast, a leading wireless power transfer company, we replace certain bands in their evaluation board (schematic [5]) and develop a customized new multi-band energy harvesting board (not over-the-shelf) that harvests RF energy at the six bands (Fig. 2). This new design maximizes the harvested energy from ambient sources through multi-band energy accumulation. By connecting and disconnecting these bands in series, we control which band contributes to the measured sum of energy. To measure the harvested energy, we use an N6705C DC Power Analyzer that can supply voltage and at the same time sink current from the harvesting board. The harvested energy is boosted using PCC210 chip to provide a regulated output voltage to a capacitor. This harvested energy can either power a backscatter tag, or a standalone low-power sensor.

4 RADIO ENERGY INFRASTRUCTURE

In this section, we explore two complementary aspects of our RF energy infrastructure: co-existing with communication systems and configuring frequency-of-operation.

4.1 Seamless Coexistence

We first focus on the coexistence mode of SCALED, which deals with the presence of ambient communication signals at a given frequency. A key challenge is that continuous transmission of the excitation signal for energy harvesting can cause severe interference for ongoing wireless communication signals. Thus, we need a smart RF energy source which can simultaneously provide RF energy to the energy harvesting devices as well as not interfere with the existing communication infrastructure. It is important to note that SCALED transmits excitation signals only at the ISM bands and vacant TV frequencies (TV whitespaces) while counting on ambient RF signals at the cellular downlink band.

Our approach: Our approach exploits the fact that our excitation signal does not need to have a specific waveform structure to enable harvesting. Thus, we ask a simple question in case of a busy channel: "Can we raise the energy level of the ongoing communication signals and reuse it for our energy harvesting purposes?" The ambient communication signals are generally very weak and cannot provide non-intermittent power to the energy harvesters specially over long-range. Therefore, our energy source switches to a repeater which amplifies the ambient signals in each band separately and retransmits them at higher power to provide continuous energy at the harvester location. It essentially only adds signal multipath to the ongoing communication signal, which can be easily handled by the communication receivers similar to commercial, FCC approved [3], WiFi extenders and cellular signal boosters. For example, commercial WiFi extenders can increase the number of potential attackers, however, WiFi-based security protocols such as WPA continue to operate and secure these networks despite the presence of such extenders. On the other hand, if the channel is found empty, we prioritize communication that may pop up, by adding extra delays before and in-between our energy transmission.

Beamforming Search: Using a simple repeater to amplify the ambient communication signals may incur its own problems. The extra path added by the repeater to the multipath propagation of the ongoing communication signal may cause destructive interference at the communication receivers rendering no reception of any data. To tackle this challenge, we implement a beamforming technique at the RF source that maximizes the RF energy at our low-power devices while also simultaneously guaranteeing constructive interference at communication receivers. To achieve this, SCALED obtains feedback from the energy harvested at different low-power devices as well as monitors the throughput and signal-to-interference-plus-noise (SINR) ratio of the data channel by simply sniffing ambient traffic. We add a phase shifter at the repeater output port, which can be tuned to enable beamforming. We note that a separate beamforming search is conducted per band.

Specifically, our repeater can monitor a channel during gaps when no energy transmission exists, to measure the current data rates achieved by incumbent users. Such passive monitoring can capture a successful transmission/reception of packets by monitoring the acknowledgments. To formulate this blind search problem, let r_j^{init} be the initial monitored data rate of an existing user j, r_j^{rep} be the data rate after turning the repeater on, and M be the number of existing users. Let θ be the phase shift that we tune at the repeater, and p_i be the harvested power for a harvesting device i. If the power at the device does not meet the threshold to report the power value, we assume $p_i = 0$. Assuming N is the number of energy harvesting devices present in the environment, our optimization problem is formulated as:

$$\begin{aligned} Opt.\ 1 \qquad & \underset{\theta}{\textbf{argmax}} \qquad \sum_{i}^{N} p_i \\ & \textbf{subject to} \quad r_j^{\text{rep}} \geq r_j^{\text{init}} \qquad 1 \leq j \leq M. \end{aligned} \tag{1}$$

An exhaustive search approach can try all possible phase shifts and pick the phase achieving the maximum harvested power while avoiding degrading the data rates of incumbent users (per the objective function above). Although this solution would find the optimal phase shift with the resolution of the chosen step size, it will cause frequent disruption to existing communication by nulling communication signals at the corresponding receivers. Therefore, a solution that can converge faster to a near-optimal phase shift value and still maintain the data rates of surrounding communication is preferable. While our empirical observations suggest that the objective function (Opt. 1) above is locally convex versus phase, we confirm that mathematically in the following derivation:

Using the Lagrange multiplier method, we convert the above optimization to an unconstrained optimization:

$$\underset{\theta,\lambda}{\textbf{argmax}}\ \mathcal{L}(\theta,\lambda) = \sum_{i}^{N} p_i + \lambda\left(\sum_{j}^{M}(r_j^{\text{rep}} - r_j^{\text{init}})\right).$$

To prove convexity, we can show that the second derivative of the objective function is ≥ 0 for all values of θ. For simplicity, we will start first with the first part which is $\sum_i^N p_i$. Let the harvested power $p_i = \eta_{\text{eff}} y\bar{y}$. While $y = x\sum_k h_k$, where x is the signal transmitted from the ambient source, y is the received version of that signal at the tag, and h_k is channel for a path k. We model the channel for different paths as the direct path channel h_d, environment reflected channel h_r, and the channel for the repeated signal h_s. Then, the harvested power at tag i can be formulated as:

$$p_i = \eta_{\text{eff}} x\bar{x}(h_d + h_r + h_s)(\bar{h_d} + \bar{h_r} + \bar{h_s}).$$

We model the channels for different path as $h_d = a_d e^{j\phi_d}$, $h_r = a_r e^{j\phi_r}$, and $h_s = a_s e^{j(\theta+\phi_s+\phi_{rep})}$. Let $h_{d\&s} = h_d + h_s$. After simplification, the second derivative of p_i w.r.t. θ is:

$$p_i^{''}(\theta) = \eta_{\text{eff}} x\bar{x} a_s \left[\overline{h_{d\&s}} e^{j(\theta+\phi_s+\phi_{\text{rep}})} + h_{d\&s} e^{-j(\theta+\phi_s+\phi_{\text{rep}})} \right].$$

It is clear that the $p_i^{''}(\theta) \geq 0, \forall\theta$. Similarly, we can show that the second part of the Lagrangian objective function is also convex, by relating a client data rate r_j^{rep} to the received signal power at that client using Shannon–Hartley theorem [47]. Through this modeling, $r_j^{\text{rep}} = B\log(1 + \frac{P_j}{N_j}) = B\log(1 + \frac{x\bar{x}\sum_k h_k \sum_k \bar{h_k}}{N_j})$. As the logarithm of a convex function is also convex, we prove that the second part of the objective function is convex.

We therefore propose a stochastic gradient ascent [44] approach. In each step, we apply the current estimate of the phase shift and in return monitor the total harvested power and the different data rates for existing users. If the gradient of the harvested energy is positive and the current data rates are not less than the initial rates, then proceed in this direction. We further note that the beamforming algorithm can be extended in the presence of multiple RF energy sources by co-optimizing phase shifts across sources.

Limiting Collisions with Comm. Sources: SCALED energy source has to avoid collision with communication transmitters by sensing the channel before sending our excitation signal. Moreover, even if the channel is currently vacant, we need to keep the access opportunity open for any communication user that may pop up. For example, in our WiFi implementation as illustrated in Fig. 3, SCALED applies standard WiFi carrier sensing (CSMA) to make sure that the channel is free, before sending its excitation signal. Additionally, in order to avoid collisions and give more priority to WiFi transmissions, SCALED leverages the Arbitrary Inter Frame Spacing (AIFS) parameter in the 802.11 standards. These standards, as the name suggests allow various traffic classes to use arbitrary waiting times as compared to the standard DIFS waiting period, before accessing a vacant channel. AIFS allows different traffic classes to have different priority levels of accessing the medium. Specifically, we set AIFS for our excitation signal transmission to be lower than the AIFS value of the lowest priority level of WiFi traffic classes. We note that even during the transmission of the excitation signal, SCALED generates continuous time gaps, where it stops transmission to give opportunities for possible WiFi users or devices to find the channel vacant through carrier sensing. Otherwise, these WiFi users will back off indefinitely waiting for the channel to be free. It is important to note that SCALED's coexistence procedure including carrier sensing, adding random delay before accessing a channel, and time gaps within transmissions can generalize well with other ISM band communication protocols such as Zigbee, BLE, LoRA, etc. For example, the BLE's adaptive frequency hopping monitors the channels and can utilize SCALED's time gaps to hop over a set of frequencies. On the other hand, SCALED can overhear BLE advertisements and avoid transmissions on advertised channel map. Our coexistence algorithm attempts to minimize interference with ongoing ISM band communication and utilize the time gaps in which channels are vacant.

4.2 Frequency Selection

In this section, we focus on selecting a set of frequencies for the excitation signal that maximizes the harvested energy at a battery-free device. In a multipath-free environment, selecting these frequencies would be as simple as choosing the lowest frequency as possible, resulting in lower path loss and higher harvested energy. However, RF energy harvesting is more prominently used in multipath-rich indoor environments. In such environments, a wireless signal can either constructively or destructively interfere at the harvesting device. Thus, a proper choice of the frequency of operation becomes an important design parameter.

Need for frequency selection To show how an optimal frequency can affect harvested energy, we conduct an empirical study in diverse indoor environments including line-of-sight (LOS) and non-LOS. We iteratively tested 20 frequencies between 2.4 and 2.5 GHz, with each frequency separated by 5 MHz and observed the harvested energy level at the harvester for every frequency. We also collected energy harvesting measurements at a particular frequency for two hours to check the temporal variation. Our results show:
(1) Optimal Frequencies are hard to find: Fig. 4(a) shows how the harvested energy levels vary across frequencies in diverse indoor environments including line-of-sight and non-line-of-sight scenarios. We observe that there are clear nulls at many frequencies confirming the requirement of optimal frequency of operation to maximize harvested energy levels. In fact, Fig. 4(b) shows that almost 30% of all the frequencies we probed result in zero harvested energy, which can lead to frequent power failures in battery-free devices. Moreover, choosing the top 3% of frequencies can increase the total energy harvested up to 1.5 times higher than what we would have obtained if we choose frequencies randomly.
(2) Optimal Frequencies change with time: Fig. 5 shows how the harvested energy changes at different times at the same frequency. We observe that even if we perform the experiment in the same environment, the optimal frequencies change with time drastically.

We conclude that to maximize the energy harvested at the device, we need to select an optimal frequency of operation. Further, iterating over all the available frequencies to choose the best frequency would introduce a large overhead since it is unstable and requires re-searching frequently, motivating the need for a new approach.
Frequency Selection Approach: Our frequency selection algorithm leverages discrete information about the total energy harvested at the device for a small set of initial frequencies. Our algorithm is based on the fact that different wavelengths arrive in different phases at the receiver. Therefore, hopping over the frequencies can result in an oscillation from destructive to constructive interference. Our algorithm searches for these frequencies that cause constructive interference and once found, it can predict what other frequencies will cause the same effect. In theory, two waves will constructively interfere if they are arriving in phase, which can happen when traveled paths for the two waves are equal in length, for example. However, this phenomenon can also happen if the difference between the two paths is an integral multiple of the wavelength. Our approach leverages this to predict frequencies that are likely to lead to constructive interference, even without the measurements at their bands.

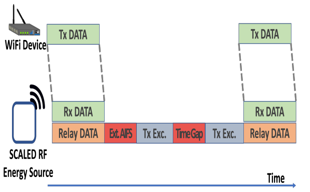
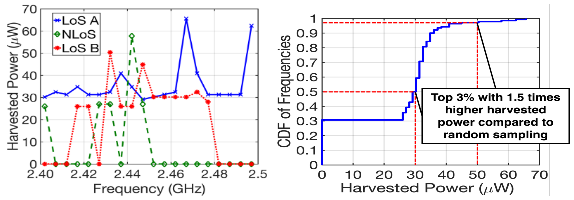


Figure 3: Seamless coexistence: Besides relaying ambient transmission, SCALED extends inter-frame spacing and adds time gaps if the channel is free.



(a) Sample Measurements (b) Percentile of Harvested Energy

Figure 4: a) Motivating empirical study: 30% of the measurements can cause power failures at the energy harvesting devices. b) Only the top 3% of frequencies have harvested power of more than 50 μW which is almost 1.5 times higher than using random sampling approaches.

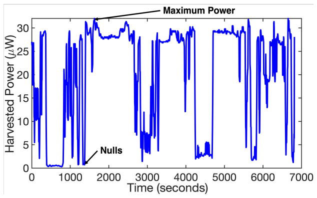


Figure 5: Time variation of the harvested power at a certain frequency.

To elaborate our approach, let us consider a transmitter sending to its receiver an excitation signal that propagates through n different paths. Let two of these paths be p_1 and p_2 through which two copies of the same signal are interfering with each other at the tag location. Given a wavelength λ of the excitation signal, we will get constructive interference at the receiver if:

$$d = |p_1 - p_2| = x\lambda$$

where $x \in \mathbb{Z}^+$, d is the path difference. This relation can be generalized to multiple paths. To see this, let us assume the difference between any pair of paths p_i and p_j is d_{ij}, then for a fixed wavelength λ:

$$d_{ij} = x_{ij}\lambda.$$

And this relation can be generalized to multiple paths if we sum all the differences between all the pairs of paths:

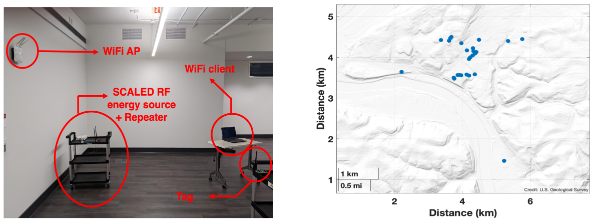
$$\sum_{i,j}^{n} d_{ij} = \lambda \sum_{i,j}^{n} x_{ij}.$$

As $\sum_{i,j}^{n} x_{ij}$ is also integer, then this sum of differences for all paths is a multiple of the wavelength. Finally, if we assume the signal takes the same paths for different wavelengths, then the $\sum_{i,j}^{n} d_{ij}$ is the same for different frequencies:

$$\sum_{i,j}^{n} d_{ij} = \lambda_1 \sum_{i,j}^{n} x_{ij} = \lambda_2 \sum_{i,j}^{n} y_{ij}.$$

The wavelengths that satisfy this equation will maximize the harvested energy at the receiver, and $\sum_{ij}^{n} d_{ij}$ is a common multiple of this set of $\Lambda^* = \{\lambda_1, \lambda_2, ...\}$.

Detailed Algorithm: Our algorithm is as follows: we start by transmitting excitation signal iteratively over randomly picked percentage of the frequencies. Based on the harvested power of these frequencies, we select a subset of them that is nearest to the received power estimated through the free path loss model. We then estimate the least common multiple (LCM) of the wavelengths corresponding to the frequencies chosen in the subset. As these wavelengths are not exactly integers, we cannot accurately calculate their LCM. Thus, to get an approximate LCM value, we scale these wavelengths by a large factor (10^7), round the scaled values to the nearest integer and then perform the LCM calculation. The resulting number is scaled down with the same scaling factor to get the approximate LCM value. The optimal wavelength (frequency) of operation would be divisors of this LCM value. As this scaling step is an approximation, we divide the estimated LCM by each wavelength, and sort the wavelengths based on the remainder of this division. The lower the remainder the nearer the frequency is to produce constructive interference, and in turn will produce higher harvested energy.



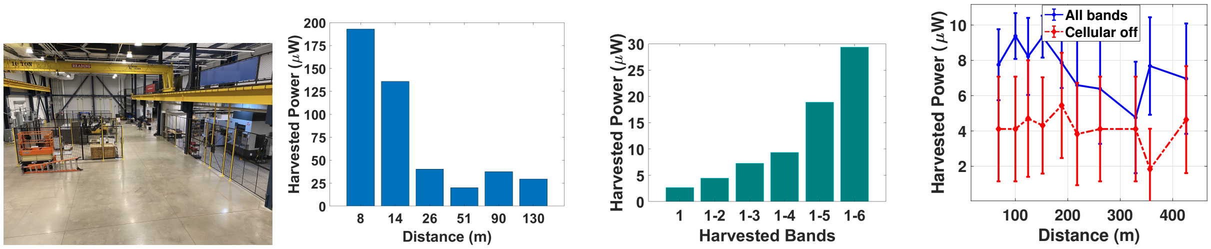
(a) SCALED's experimental setup (b) A map of our experiment locations.

Figure 6: Experimental setup and locations

We apply our algorithm individually on 3 bands - TV whitespaces, 900 MHz and 2.4-2.5 GHz ISM band and sort the frequencies in these bands based on their expected harvested energy. Based on the source energy budget, range to the device and the environment, SCALED implements the water-filling algorithm [36, 42], to select the most rewarding frequencies over these multiple bands. Thus, as opposed to exhaustively using frequencies across all bands, we limit SCALED's footprint and energy needs. We note that in the interest of scalability over many harvesting devices, SCALED runs its frequency selection algorithm iteratively over all devices, in case more than one harvester is present in the environment. We note that we select the most rewarding frequencies to be repeated or, if vacant, to be transmitted by our energy source. We also acknowledge while searching for the set of frequencies and beamforming phases, the performance of our system is not optimized. We investigate the convergence latency of these algorithms in Sec. 6

5 IMPLEMENTATION

We implement SCALED using an Ettus USRP N210 as the RF energy source with no carrier sensing and a customized multiband energy harvesting board. Our customized board counts on the PCC110 RF-to-DC converter and the PCC210 Boost Converter with high efficiency power conversion reaching 75%[6]. To implement carrier sensing and update AIFS parameter, we use a commercial WiFi



(a) Industrial Setup (b) Indoor Range (c) Indoor Multiband Effect (d) Outdoor Range

Figure 7: a) Industrial setup where we place our RF source and energy harvesters at the two ends of the building. b) Indoor achievable range of energy harvesting over the six bands. c) Effect of adding more bands to the energy harvester (over 130 m). d) Outdoor harvesting range over the six bands.

chipset acting as our polite RF energy source. To harvest simultaneously through multiple bands, we modify the harvesting board by adding jumpers to selected bands. We use LP0410 antennas for the TV whitespaces, and omni-directional WiFi 2.4 GHz antennas (9 dBi gain). To boost the power limited USRPs, we use commercial FCC approved power amplifiers for WiFi [1] and TV whitespaces. Our repeater consists of two WiFi antennas, the VBF-2435+ Band Pass Filter (2340 to 2530 MHz), HMC631LP3E phase shifter and the ZX60-272LN-S+ low noise amplifier.

We use the hostapd Linux tool to update AIFS of this WiFi chipset to act as the polite RF source. We use a micro-controller (Arduino Uno) to measure the harvested energy after setting the harvesting board to measurement mode. We transmit our excitation signal through the USRP using UHD/C++. Further, we use the iperf tool for active network measurements to transmit continuously when we use the WiFi chipset as RF energy source (see Fig. 6(a)).

We evaluate our system in diverse line-of-sight and non-line-sight indoor and outdoor environments (see Fig. 6(b)) while spanning the excitation transmission space over TV white spaces at 470-698 MHz, 902-928 MHz, and 2.4-2.5 GHz ISM bands. We measure the effect of our RF energy transmission on the throughput between a PC and a commercial WiFi router. For indoors, we evaluated our system in two settings: industrial and academic environments. In each setting, we build a diverse testbed spanning 12 different locations. Through wardriving outdoors, we evaluate the range of our system by measuring the harvested energy to the nearest cellular tower. We plan to open-source our implementation and make our 111,000 sample dataset publicly available.

To achieve the maximum coverage, SCALED selects the optimal frequency that maximizes the harvested energy and sets the transmit power to be within the FCC limits. In this paper, we do not explore the problem of energy source placement as the optimal deployment of transmitters in general to maximize coverage is well studied in the literature [20, 21]. This literature spans the maximization of coverage for both wireless communication [10, 21] and RF energy transfer [20].

6 EXPERIMENTAL RESULTS

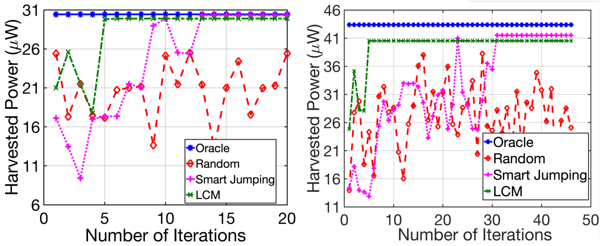
6.1 Multiband Harvesting Range

Setup: We explore the harvesting range, i.e., the maximum distance between the energy source and the harvester, indoors and outdoors. For indoors, we vary the distance between the RF energy source and the energy harvester in an industrial setting (Fig. 7(a)) from 8 m to 130 m (maximum distance to try inside this facility). We place our RF energy source at the beginning of a long corridor and our energy harvester at the other end of the building to reach the maximum possible line-of-sight distance. We show here that transmitting the excitation signal simultaneously at three TV whitespace bands (520MHz, 570MHz, 620MHz), WiFi and an RFID reader [4], while still counting on ambient cellular signals can significantly improve the range. For outdoors, and due to logistical challenges in deploying new large base stations across city locations, we leverage existing cellular base stations as energy sources and count the distance between our harvester and the nearest base station as the outdoor range. Our energy harvester is setup in all experiments to accumulate energy from all six bands (mentioned in Sec. 3), except here in this outdoor experiment we switch on and off the LTE band, to evaluate the range of the nearest base station.

Results: Fig. 7(b) illustrates that multiband energy harvesting from carefully selected frequency bands can achieve 29 μW over 130 m. It is important to note that we can achieve a longer range for a lower energy limit. Moreover, Fig. 7(c) shows that adding up a frequency band at a time can improve the harvested energy significantly while fixing the distance to 130 m between the energy source and the harvester. The band numbers shown on X-axis correspond to the ones shown in Fig. 2. Moving to outdoors, Fig. 7(d) shows that only adding a single frequency band (cellular in this scenario) nearly doubles the average harvested energy even at locations where the nearest cellular base station is over 400m from the harvester. It is expected that the harvested energy decays away from the base station, but building blockages and the multipath effect impacts this trend at some locations.

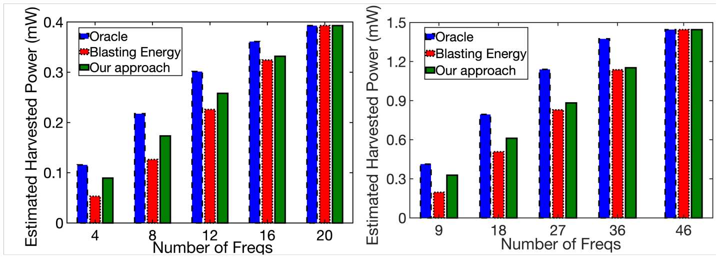
6.2 Frequency Selection

Setup: In various indoor environments, we conduct the following static experiment: we use a USRP as the RF energy source, and an over-the-shelf harvesting board to harvest energy from different locations. The RF energy source hops over the frequencies starting from 2402 MHz to 2497 MHz (WiFi) and from 470 MHz to 698 MHz (TV whitespaces). For each frequency, SCALED transmits a sine wave for 20 seconds, then waits for 10 seconds to hop to the next frequency. An example of the collected data is shown in



a) WiFi b) TV Whitespaces

Figure 8: Convergence of our frequency selection algorithm compared to baselines.



a) WiFi b) TV Whitespaces

Figure 9: Efficiency of our frequency selection algorithm compared to baselines.

Fig. 4(a). In terms of convergence, we compare our least common multiple algorithm (LCM) with three baselines: (1) *Oracle*, which can correctly sort the frequencies based on the harvested energy without initially trying any set of frequencies, (2) *Random*, which randomly picks a frequency and transmits at each iteration, (3) *Smart Jumping*, which iterates over half of the search space, and transmits an excitation signal on each of these frequencies trying to learn a pattern, and then jumps to a small set of the remaining frequencies. Based on the same experiment, we also consider the case of the energy source using multiple frequencies simultaneously. We show how our algorithm compares, in terms of cumulative harvested energy, to an oracle that can correctly pick the most rewarding subset, or the second baseline that blasts energy within the first portion in the search space.

Results: Fig. 8 shows how our LCM algorithm converges after the fourth iteration (note that one iteration = 20-50 ms depending on the tag's startup time) to an average of 29 μW near the most rewarding frequency (30 μW) vs. random hopping that spans the whole frequency space and obtaining on average 25 μW. Similarly, in TV whitespaces, LCM converges to 40 μW on the fifth iteration compared to the optimal frequency achieving on average 43.5 μW. Fig. 9 shows how our LCM algorithm can approximately sort the frequencies based on their harvested energy and achieve near-optimal accumulated harvested energy. We emphasize that each approach transmits the same amount of energy, yet SCALED offers superior energy harvesting efficiency.

6.3 Seamless Coexistence

Setup: To evaluate how SCALED coexists with ongoing WiFi communication, we show here how the throughput changes between an ambient laptop and WiFi access point (on the same shared frequency band), while varying the distance between our energy source and the WiFi receiver. We compare SCALED and several baselines: (1) *Only WiFi:* no energy transmission (i.e., only the WiFi radio operates); (2) *Continuous Energy:* a USRP that continuously blasts energy without carrier sensing. (3) *Carrier sense:* A WiFi chipset that can perform carrier sense with the same AIFS priority as regular WiFi transmitters. (4) *Polite Carrier Sense:* A transmitter that uses AIFS to give a higher priority to other WiFi transmitters. (5) *SCALED:* The coexistence module of SCALED (Polite Carrier Sense + Repeater), that also repeats and beamforms ambient WiFi signals when the channel is sensed to be busy.

Results: Fig. 10 illustrates how SCALED injects excitation signals and repeats ongoing ambient WiFi transmissions without degrading their throughput. Continuously blasting energy can clearly halt any ongoing WiFi transmission as shown in the figure. More importantly, carrier sensing only can avoid collisions with WiFi users but also shares the medium fairly with them, resulting in a clear drop of WiFi throughput. When we give more priority to WiFi transmissions than our RF energy source, the throughput is similar to that of the WiFi only mode. However, as explained earlier, counting only on polite transmissions that fill WiFi gaps would feed our devices with extremely low energy compared to adding the repeater to our system. Therefore, we show here how a polite energy source with a smart repeater (i.e., SCALED) achieves the best of both worlds – feeding more energy to surrounding devices without degrading the WiFi throughput significantly.

6.4 Beamforming Search

Setup: In this experiment, we evaluate our phase shift search algorithm that searches for a phase shift that maximizes the harvested energy, while not decreasing WiFi data rates. We measure the throughput over a standard WiFi link between an access point and laptop using iperf. Next, we use a SCALED repeater with a phase shifter to provide energy to the harvesting board. To evaluate the blind beamforming task, we compare our stochastic gradient ascent algorithm to an oracle that can find the highest energy harvested while preserving the ambient WiFi link's data rate. We also show a baseline algorithm that picks randomly chosen phase shifts repeatedly until it can preserve the WiFi link's data rate.

Results: Fig. 11 shows that a greedy gradient ascent with random initial guesses can converge after 6 iterations to the optimal phase shift that still satisfies the data rate constraint. Each iteration is limited by the startup time (20-50 ms) of the tag [7, 16]. We observe that SCALED's approach indeed reaches the optimal harvested power achieved by the oracle. In contrast, the random baseline can often get stuck in local optima that violate the WiFi data rate constraint, resulting in poor convergence time.

6.5 Impact of Repeater on WiFi Users

Setup: This experiment studies the effect of our repeater on the throughput of surrounding WiFi communication. We conduct an experiment in an indoor space that includes a WiFi access point

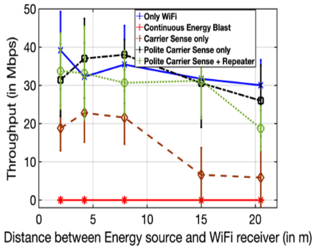


Figure 10: Effect of our RF energy source on the throughput of WiFi transmissions.

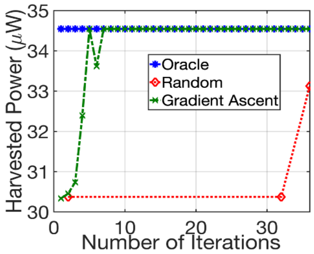


Figure 11: Convergence of our blind phase search to beamform at the harvester while not decreasing WiFi throughput.

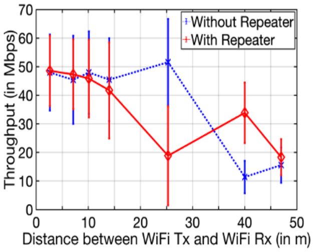


Figure 12: Effect of the presence of Repeater on the throughput of WiFi Tx and Rx link.

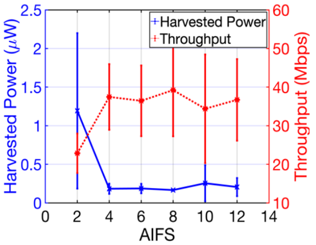


Figure 13: Effect of increasing time gaps between our RF source transmission on the harvested energy and the throughput of a WiFi user.

and a laptop without other WiFi networks. We use our repeater to repeat the transmitted signal on this WiFi link without employing beamforming, and show how this repeated signal can affect the WiFi throughput. We change the location of the WiFi laptop to vary the distance to the access point and the distance to the repeater.

Results: Fig 12 depicts the effect of the repeater only, without applying any phase shifts, on the throughput of WiFi communication. From this figure, we observe that the repeater by and large does not affect the performance of WiFi communication except for some cases where it may either improve or degrade the throughput. We surmise these changes are due to constructive or destructive interference from the additional signal path that the repeater's presence creates. Significant throughput degradation happens at the distance of 25 m, as in this case, the WiFi receiver and the repeater are in close proximity, which results in saturation of the WiFi channel. We resolve a degradation in the throughput by applying our beamforming algorithm using a phase shifter to actively null our transmission below the saturation level at the receiver. Interestingly, the repeater alone, while feeding extra energy for harvesters, can sometimes improve the throughput of WiFi signals, especially when the repeater exists in between an access point and a distant WiFi user.

6.6 Effect of Varying Time Gaps

Setup: This experiment shows how gaps between our energy source's transmissions impact ambient WiFi's throughput and the harvested energy. A laptop represents SCALED's energy source, which varies AIFS through hostapd and sends WiFi packets at a fixed channel. A WiFi access point and client (another laptop), record throughput as our energy source transmits.

Results: Fig. 13 shows the trade-off between WiFi throughput and the harvested energy while varying AIFS. We start from giving the same priority to WiFi and SCALED to gradually giving more priority to WiFi. In doing so, we see that the WiFi throughput improves significantly to nearly double. In contrast, the harvested energy decreases as we increase these time gaps. This shows the importance of including the repeater in our system to boost ambient WiFi energy, so that SCALED can continue to power the harvesting devices. It also shows the importance of deploying the RF energy source to avoid excessive dependence on ambient WiFi.

7 RELATED WORK

Infrastructure-Assisted Energy harvesting: In this category, dedicated infrastructure (generally a transmitter) provides RF energy to a battery-less device. Some examples are - RFID [43] and NFC [18] technologies, which use dedicated readers/transmitters to power a battery-less tag and communicate. In recent years, much work in the RFID and NFC contexts either improve their communication capabilities such as range [31, 45, 51, 52], speed [9, 40, 46], robustness [8, 15, 29] or develop new localization and sensing paradigms [24, 53]. Another body of work focuses on designing distributed charging for short range dedicated wireless power transfer [14]. Similarly, prior work designs wireless power transfer architectures for cellular networks [23]. However, these transmitters either have dedicated bands or can interfere with ongoing wireless communication, leading to low communication throughput and efficiency. PoWiFi [49] modified Wi-Fi routers for power delivery and normal Wi-Fi communication simultaneously without causing interference, but this requires hardware access to existing transmitter and is hard to adapt to wider bands.

SCALED is also an infrastructure assisted energy harvesting system which requires a dedicated RF energy source to power up battery-free devices. However, this energy source supplements ambient energy, is polite and never interferes with the existing communication infrastructure. A simulation model for MAC layer in RF energy harvesting was developed in [28], but SCALED is the first system implementation which we know of.

Ambient Energy Harvesting: To remove the dependence on a dedicated transmitter, researchers developed systems which take advantage of the existing communication infrastructure already present in the environment. Work done in this context includes using ambient TV, FM, WiFi and LoRa transmissions [11, 13, 26, 27, 30, 38, 41, 50] to power a battery-less device. However, these transmissions are extremely irregular leading to frequent discharging of the device. This makes it necessary to operate close to the transmitter [12] and allows for intermittent behavior in our devices [22, 54]. In other words, past work focuses on the choice between ambient RF energy harvesting and non-intermittent operation, unlike SCALED.

Repeaters in Energy Harvesting techniques: There has been a vast literature on using repeaters to increase the range and efficiency of energy harvesting systems. Some of them use analog relays [19, 33], which simply amplify the received excitation signals and transmits them again, while others use more complex digital relays [35, 48], which decode and then re-encode the received excitation signals to transmit them at full power. However, in both such works, the relays were introduced only to increase the performance of energy harvesting system. In contrast, the SCALED repeater only mimics the *ambient* transmissions in the environment and is turned off during the dedicated transmitter mode.

8 CONCLUSION

This paper presents SCALED, which takes an important step towards extending the range of RF energy harvesting. SCALED achieves by designing a multi-band energy harvesting platform, supplementary RF energy delivery infrastructure. A detailed implementation and evaluation of SCALEDshows improved energy harvesting performance and reliability, without compromising communication radio data rates. We have designed SCALED using off-the-shelf components.

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