# Sifting Through the Airwaves: Efficient and Scalable Multiband RF Harvesting

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***Abstract*—Harvesting ambient RF power is attractive as a means to operate microelectronics without wires, batteries, or even a dedicated RFID reader. However, most previous ambient RF harvesters have been narrowband, making mobile sensing scenarios infeasible: an RF harvester tuned to work in one city will not generally work in another, as the spectral environments tend to differ. This paper presents a novel approach to multiband harvesting. A single wideband antenna is followed by several narrowband rectifier chains. Each rectifier chain consists of a bandpass filter, a tuned impedance matching network, and a rectifier. The outputs of the rectifiers are combined via a novel diode summation network that enables good performance even when only a subset of the narrowband harvesters is excited. These techniques make ambient RF harvesting feasible for mobile applications. The techniques can potentially enable applications such as ambient RF-powered data logging sensors that upload data to RFID readers when in range.**

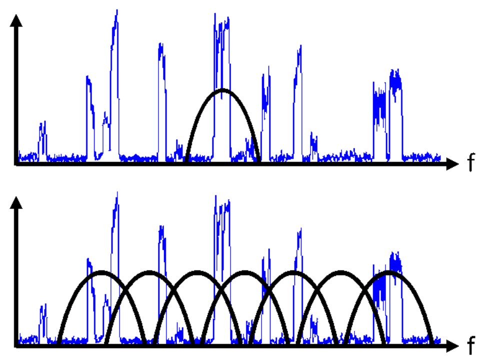



Fig. 1. A single-band harvester cannot efficiently collect energy over a large bandwidth. The proposed multiband harvester aims to divide and conquer an arbitrarily large bandwidth for efficient harvesting.

## I. Introduction

Ambient radio harvesting is a promising approach to powering battery-free sensing, computing, and communication devices[1], [2], [3]. The vanishingly small amount of power now required by modern microelectronics,[4], [5] along with new low power communication techniques such as those described in [6], make ambient radio harvesting an increasingly viable power supply option. Compared to solar power, ambient RF has the advantage of being available at night, and is attractive from an industrial design perspective: the antennas already used in mobile devices for communication purposes can potentially become a power source, without requiring any changes to the form factor or appearance of the device.

However, there still exist crippling roadblocks preventing widespread adoption of ambient RF harvesting as a power source. Conventional RF harvesting methods are only capable of extracting power from a narrow spectral band. The supply will cease to provide power when its particular source band is not available, either due to geographical fluctuations in spectral occupation, occlusion and shielding (e.g., from the walls of a building), or simply from multipath fading of the ambient signal. When starved of its energy source the device must cease to operate, limiting the application space mostly to a small geographical area with line-of-sight to an ambient radio source of interest.

Some work has been done on wideband harvesting[7], tunable harvesting[8], and multiband harvesting[9], [10]. While wideband harvesting can capture energy across a large swath of spectrum, it typically results in very low efficiency at any particular source frequency as the quality of the impedance match between the antenna and single rectifier must reduce as the bandwidth increases[11]. Tunable harvesting allows a system to dynamically select a band of interest based on spectral availability, and therefore promises to be able to provide efficient rectification of signals from a single source, regardless of the frequency of that source. However, tunable harvesters in battery free systems will require solving the very difficult bootstrapping problem to allow the system to cold-start, and also will ignore energy outside the band to which they are tuned.

Multiband harvesting involves building an array of harvesters, each tuned to an adjacent but orthogonal frequency band, and has the benefit of being able to capture power efficiently from multiple bands at once. Existing work on multiband harvesting typically makes use of multiple antennas, each tuned to a band of interest, and each feeding an independent rectifier through a tuned matching circuit[9]. In existing work, the DC output from each rectifier is usually then serially combined to produce a voltage sum which becomes the multiband harvester output.

This work aims to produce a more practical multiband harvester, which does not require multiple antennas. A single wideband antenna feeds a trunk node which is electrically split into independent branches by orthogonally tuned bandpass filters. Each branch is then impedance matched to an independent rectifier, and the rectifier outputs are summed at DC by a novel method.

In the remainder of this paper, the novel single-antenna multiband harvester is presented and design choices are described and defended. A strategy is presented for computing and optimizing bandpass filter and impedance matching values to produce an efficient system. A method is presented for efficiently summing many independent rectifier outputs using a network of diodes. Simulations are performed for an eight-band harvester and used to explore the design tradeoffs for this

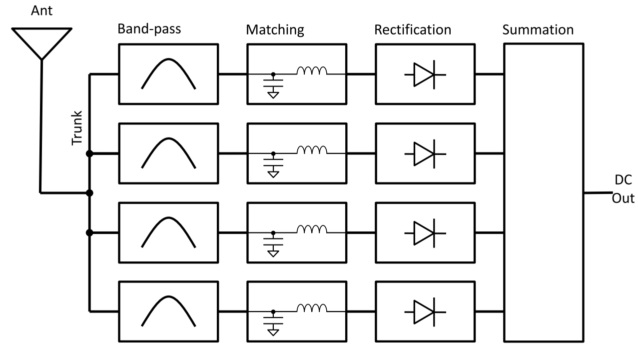



Fig. 2. The topology of the proposed multiband harvester. A single wideband antenna is used, in contrast to other work. Bands are spaced geometrically with a frequency ratio R.

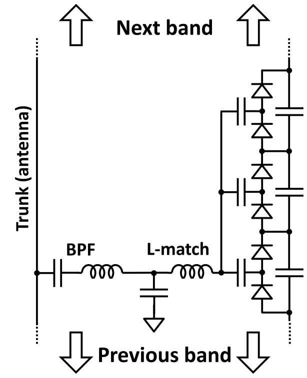



Fig. 3. One band in the proposed multiband harvester. Diode summation network is omitted for clarity. The trunk node is connected to the antenna in the full system.

system, and both a two-band and a five-band prototoype are developed and characterized.

## II. Multiband Harvesting

The multiband charge pump topology presented here is based on the Dickson charge pump, a circuit commonly used in RF-DC conversion which provides both rectification and impedance transformation[12]. The unique aspect of the design presented here is the ability to capture power from multiple bands, and combine this power in an optimal way for any combination of excited bands. Figure 2 illustrates the architecture of the proposed method and Figure 3 shows the circuit topology for a single band of the harvester.

Our multiband harvester covers N adjacent frequency bands, each with an M stage Dickson charge pump providing rectification and voltage multiplication. The number of bands (N), the geometric spacing of the band frequencies (R=$\frac{f_n}{f_{n-1}}$), and the number of stages for each band are all key parameters of the design space.

One departure from existing work is that this parallel harvester topology is designed to provide a good match to one single-port antenna at multiple bands, whereas most published multiband harvesting topologies make use of multiple antennas, each covering a particular band of interest[9], or make use of dual-band antennas with multiple ports and a single rectifier[10]. Therefore, in contrast to existing work, this system can scale to a large number of frequency bands with no additional antennas or antenna ports required. We imagine this system being useful as a universal solution for RF energy harvesting implementations, especially if scaled to a large number of frequency bands (and therefore acting as an efficient harvester across a very wide bandwidth). With such a universal harvesting solution, the choice of antenna then becomes the sole responsibility of the application developer.

Another departure from existing work is in the method of combination of the harvester DC output paths. Most existing multi-harvester systems use a simple serial connection between independent rectifiers, a topology which, in the context of multiband harvesting, only provides high efficiency in the case where all bands are excited. If one or more bands in such a serially connected system are not excited, the diode drops in the unexcited bands' charge pumps must be overcome by the other bands, resulting in a major efficiency degradation. Our solution is to use "shortcut" diodes to bypass the bands which are not active, thereby allowing an automatic optimal configuration to be achieved in summing the voltages produced by each band rectifier. These shortcut diodes ideally have both low threshold and low leakage, attributes which are very achievable as they will be operating at DC.

### A. *Two multiband harvesting paradigms*

We envision that frequency band selection for the multiband harvester may follow one of two possible paradigms, depending on intended application:

1) A multi-protocol arrangement targeting several commonly used bands. For instance, 433 MHz, 915 MHz, and 2.45 GHz could be simultaneously targeted.
2) A tightly packed arrangement for efficient harvesting over a very wide bandwidth. This arrangement allows any number and placement of RF signals to be efficiently harvested, provided they are within the design bandwidth.

The first paradigm leverages knowledge of commonly occupied portions of the spectrum, which will be most likely to yield power. This method could achieve high practical efficiency with low complexity, as the number of target bands could be relatively small.

The second paradigm allows the harvester to capture energy at nearly any frequency in a large prescribed bandwidth (e.g., the 267-1350 MHz bandwidth targeted by our prototype). This has potential to become a universally applicable and future-proof method, as it doesn't rely on knowledge of commonly occupied bands, or on current details of regulatory spectral allocation.

## III. Design strategies for a multiband harvester

The multiband harvester consists of a single wideband antenna feeding an array of harvester bands, each of which is designed to target a particular frequency range. We select the center of this intended range and refer to this as the "design frequency" for each band. We have explored two challenges in implementation of such a harvester: Tuning strategies for optimizing harvesting efficiency, and power combination strategies which allow simultaneous extraction of power from many bands.

### A. Tuning

The tuning of the parallel-connected filtering and impedance matching networks which feed independent rectifiers is a very high dimensional problem and perhaps the most unique and interesting challenge in developing this particular multiband harvesting system.

In this work, we consider phrasing this tuning challenge as an optimization problem with a carefully designed cost function. The cost function used here is based on two main factors:

1) We aim to minimize reflected energy in matching the antenna to the trunk of the multiband harvesting network. In other words, the sum of S11 at each design frequency should be minimized.
2) We aim to minimize the impact of adjacent harvester branches on the impedance of the network at each band's design frequency. In other words, for each design frequency, the impedance of adjacent bands is maximized.

In our proposed optimization strategy, a weighted combination of the above terms could be minimized to select the bandpass filter and match network values for each band of the harvester.

The decision to minimize overall S11 at each design frequency while maximizing adjacent band impedance can be illustrated by considering a scenario in which only a single continuous wave is presented to the multiband harvester. If we simply minimize overall S11, the power of this continuous wave may end up distributed over several consecutive rectifiers, resulting in several very poorly excited rectifiers and therefore a very inefficient system. To also minimize the match quality of adjacent bands means that, instead of distributing this continuous wave's power, we focus this power on one rectifier and thereby maximize the efficiency of the system in harvesting that continuous wave signal.

Since most ambient or intentionally radiated signals are relatively narrow bandwidth compared to the overall scope of our harvester, most sources will excite only one of the bands of the harvester and therefore support the logic of this optimization strategy.

A heuristic for achieving these tuning goals involves making the simplifying assumption that the bandpass filter is a short when resonant and an open otherwise, and to design the matching network given this simplified model of the bandpass filter. The resulting match network values in this method are the same as those for a single-band harvester, and it is simply the addition of the bandpass filters which enables efficient multiband operation. We make use of this simplified method to tune the prototype harvesters in section V.

A simple lumped element model of the harvester was developed in MATLAB. The model makes use of rectifier impedance measurements taken from actual prototypes; each rectifier in the multiband harvester must be characterized at each of the design frequencies in order to achieve a realistic model of the harvester. A simplified model of the antenna is used in which impedance is a constant 50 $\Omega$ across the entire band of interest, which allows for simplified experimentation. Although this will not accurately represent the frequency-dependent impedance of a real antenna, it's conceivable that in future work the antenna impedance could be measured across the operating bandwidth and used to better tune the system.

First approximations for the bandpass filter and L-match network values for each band are forward-computed by assuming each band is independent and simply selecting the values which achieve minimal S11. This is a first guess, and could ultimately be used as the seed value for an optimizing search based on the strategy described above. The resulting match values would be bandpass and L-match network values which minimize overall S11 at each design frequency while minimizing interaction between adjacent bands, as described.

### B. Overcoming impedance matching limits

The Bode-Fano theorem describes the limits of impedance matching between a source and one complex load[11]. In conventional single-band RF harvesters or wideband harvesters, the bandwidth over which the antenna can be well matched to a single rectifier will be limited, therefore placing an upper limit on the size of the band over which the RF-DC conversion will remain efficient.

We hypothesize that the multiband harvester topology presented herein may be able to circumvent the Bode-Fano limit by allowing the match to effectively be distributed across multiple loads.

There are at least two impedance interfaces in the multiband system that need to be well-matched for efficient RF-DC conversion at a given frequency. The first is the interface between the antenna port and the trunk node of the multiband harvester. The second is the interface between the trunk node and the load (rectifier) for each of the branches.

The Bode-Fano theorem only places a limit on match bandwidth for complex sources and/or loads. It will certainly model the limitations of the match between the trunk and the rectifier for each branch, since the rectifier impedance will always be complex. However, the antenna-to-trunk interface can be designed such that the impedance looking into each bandpass filter at it's resonant frequency is real and matched to the antenna. Because the adjacent branch bandpass filters are assumed to have negligible admittance at the design frequency of any given band, they ideally will not contribute significantly to the impedance viewed from the trunk node at adjacent bands.

In summary, we hypothesize that each branch of the harvester will be Bode-Fano-constrained, but that the antenna-to-trunk match (and therefore the system as a whole) will not be constrained.

### C. Power combining

Most existing multiband systems simply serially combine the output of each band. This naive approach has a major flaw: low efficiency in most real-world use cases! Most existing systems are developed and tested under the assumption that all bands will be excited at all times, and in those cases may perform very efficiently. However, not all frequencies in the radio spectrum are inhabited in all locations and at all times. When one (or more) bands in these systems remains unexcited, the diodes in the unexcited band's charge pump now represent an obstacle to current flow from the excited bands. These "dead weight" diodes can drop significant voltage and severely impact efficiency.

With this work we contribute a method of power combination which allows summation of power from multiple harvesting bands, regardless of whether they are all excited.

In the first approach, we simply consider bypassing these "dead weight" diodes with a single low threshold, low leakage DC diode. This topology reduces the extra overhead of the unexcited bands, but still has significant overhead if there are many unexcited bands (and therefore many bypass diodes for current to traverse).

The second approach involves placing "shortcut" diodes between each serially-connected band output and the two output rails. This method reduces the efficiency hit caused by the bypass diodes in the first approach, but doesn't fully achieve optimal power combination in all cases. For instance, if the first and second bands are excited the output voltage will be near their sum (minus diode drops), but if the first and third bands are excited the output voltage may be as low as the maximum of the two band outputs, effectively throwing away the benefit of the second excited band.

The third approach addresses these challenges by allowing the output to attain the sum voltage of all excited bands, regardless of whether the excited bands are contiguous or scattered throughout the harvester array. This is implemented by simply connecting each node in the harvester stack to every other node with a properly oriented, low threshold and low leakage DC diode. The output in this topology will be the sum of all excited bands, minus some number of diode drops which depends on the number and arrangement of bands excited. This is the power combination topology used throughout the simulated and experimental results herein.

The leakage current of so many DC shortcut diodes must be considered when implementing a multiband harvester with a large number of bands. However, while the total number of DC shortcut diodes in the system can grow large as the number of bands increases, the leakage wont scale quite as geometrically, as the average of the reverse voltage across a diode in the system will decrease as the number of bands increases (given some number and arrangement of excited bands).

### D. Scaling considerations

Scaling the multiband harvester to a large number of bands seems increasingly difficult for implementation with discrete components. As the number of bands increases, the component count also increases (including the shortcut diodes), and so the overall size of the multiband array becomes significant with respect to the wavelength and therefore the lumped modeling done here is not sufficient. Distributed modeling will likely be needed for multiband harvesters with a large band count, significantly increasing the complexity of modeling and the difficulty of tuning the harvester.

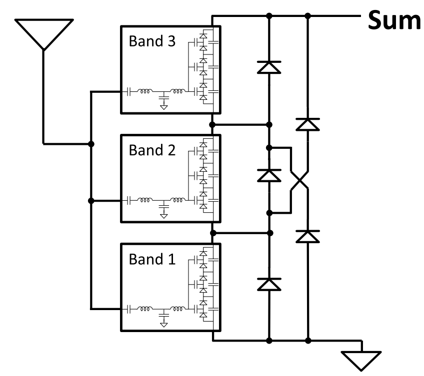



Fig. 4. An example of the summation network, shown here for a 3-band harvester. The output voltage will be the global sum of the band outputs, less a small number of diode drops.

The frequency spacing between bands of the multiband harvester is a critical design parameter. Closely spaced bands exhibit more interaction and are therefore less efficient, particularly with the low Q bandpass filters achievable with discrete components. However, distantly placed bands can leave large gaps in spectral coverage, where RF-DC conversion efficiency will be low. We hypothesize that there is an optimal frequency ratio between bands given a particular bandpass filter Q value, but exploring this tradeoff is outside the scope of this paper.

## IV. Simulating the Multiband Harvester

To explore the feasibility of this multiband harvesting concept, a SPICE model of a multiband harvester was constructed and subjected to some virtual experimentation. First, a single band model was constructed using Avago HSMS-285C diode models in a 3-stage Dickson charge pump arrangement. The impedance of the single band charge pump was measured at each of the design frequencies for the system. Eight bands in the UHF region of the spectrum were selected: 300 MHz, 356 MHz, 423 MHz, 503 MHz, 597 MHz, 709 MHz, 842 MHz, and 1 GHz. A first order LC bandpass filter was generated at each design frequency (with a Q of 5) and used to isolate the eight bands. A low-pass L-match network was then constructed for each band, to match the 50 Ω source to the load impedance of each band's rectifier at its design frequency. All values were forward-computed based on initial simulated impedance measurements; no iteration was performed once initial component values had been selected.

A diode summation network was also constructed using the SPICE model for the SDM03U40 Schottky diode manufactured by Diodes, Inc., and used to sum the DC output power from each of the eight bands. The output of the summation network was connected to a 100 kΩ load resistor to simulate a device being powered.

### A. Single-tone response

Figure 5 shows the RF-DC conversion efficiency as a function of frequency for a single-tone excitation. The intended design frequencies align well with the conversion efficiency peaks, though there is significant variation in the conversion efficiency between bands. The fact that the outer bands are more efficient is a hint that a varying amount interaction between bands may be the cause of the efficiency variation. Bands near the center will always experience more interaction with adjacent bands than those near the outside of the targeted range.

### B. Simulated multi-excitation and summation

To characterize the effectiveness of the summation network and its impact on the multiband harvester, a series of tests were done on two systems: One with the summation network in place, and one with only a simple serial connection between bands. The two systems were otherwise identical.

Eight simulated voltage sources were connected serially to generate up to eight excitation tones. The eight sources were modulated in a binary-weighted fashion, turning on or off each source to ultimately produce every possible combination of excited bands (eight bands yields 256 permutations). The source power per band was set to +3 dBm for this simulation. A transient simulation was performed for each combination of excited bands, and the summed output voltage was measured after a fixed stabilization period had expired.

Figure 6 characterizes the summation performance of the harvester, plotting DC power delivered to the load resistor as a function of the number of excited bands (where all bands are excited with equal power).

Power combines somewhat linearly, with each additional band contributing approximately 750 $\mu$W to the sum output power on average. Note that for each permutation of excited bands, the output power will vary for two reasons: The first is that the RF-DC conversion efficiency for each band is not equal. The second is more subtle; the diode summation network will exhibit a different operating efficiency depending on the arrangement (not simply the number) of excited bands.

This arrangement-dependent summation efficiency can be shown by comparing the case in which only bands 1, 3, and 5 are excited to the case in which only bands 1, 2, and 3 are excited. In the former case, multiple shortcut diode drops must be overcome between the excited bands, while in the latter case the bands are adjacent and therefore sum serially with no diode drop between them.

Figure 7 illustrates the performance improvement seen (in terms of delivered power) when the diode summation network is added. On average the summation network provides a significant benefit, though there are a number of test cases in which the presence of the summation network reduces overall efficiency. We hypothesize that this can be attributed to the reverse leakage current of the summation diodes, which becomes a significant factor with the large number of diodes required to implement the network.

## V. Prototype Design and Characterization

A 2-band and 5-band prototype are implemented with discrete components, as shown in Figure 8(a) and 8(b). The prototypes use 3 stage Dickson charge pumps in each band, use the described ”shortcut” summation topology, and when the experiment requires they are connected to a wideband log-periodic antenna with a roughly 6 dBi gain. The two-band harvester design frequencies are 539 MHz and 915 MHz, and target an ambient television signal near our campus and

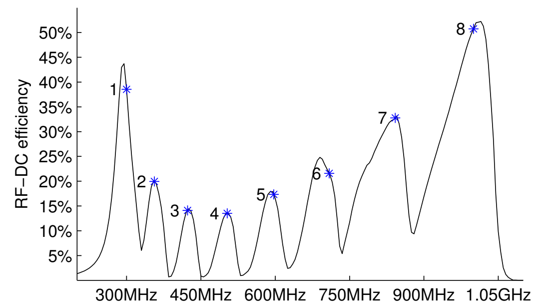



Fig. 5. The RF-DC conversion efficiency of the simulated 8-band harvester, including the diode summation network. Design frequencies for each band are shown.

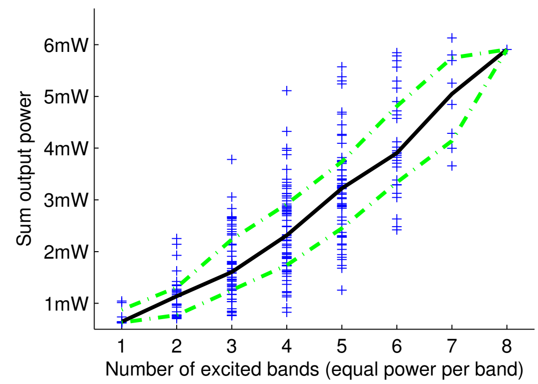



Fig. 6. For the simulated 8-band harvester: Power delivered to the load through the diode summation network for every permutation of excited bands. Different number and arrangement of excited bands impacts how well they can be summed. Median and lower and upper quartile of the results are shown.

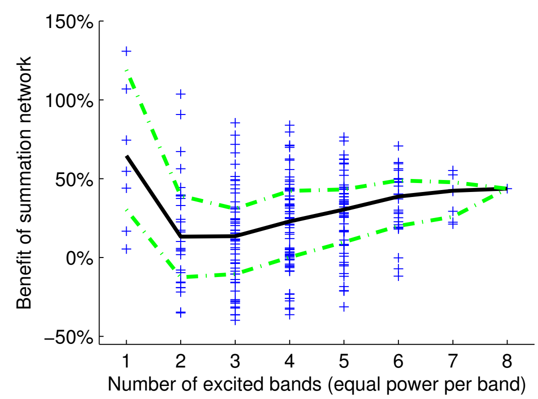
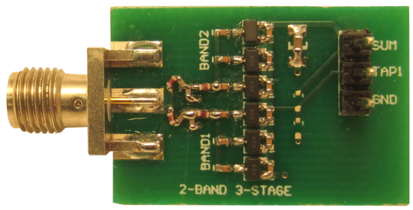


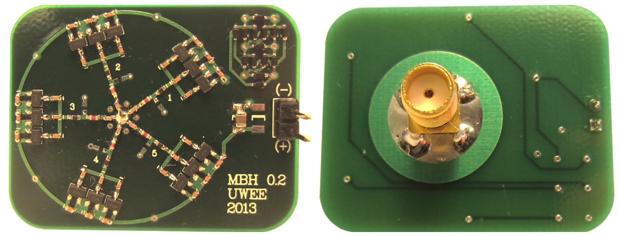

Fig. 7. For the simulated 8-band harvester: Improvement in power output when the diode summation network is used, for every permutation of excited bands. Median and lower and upper quartile of the results are shown.

an RFID reader, respectively. The five-band harvester design frequencies were chosen by selecting a fixed ratio of 1.5 between adjacent frequency bands, and are 267 MHz, 400 MHz, 600 MHz, 900 MHz, and 1.35 GHz.

Avago HSMS-285C Schottky diodes are used in the 3-stage RF-DC conversion charge pumps. The summation network makes use of low-threshold and low-leakage SDM03U40 diodes manufactured by Diodes, Inc.

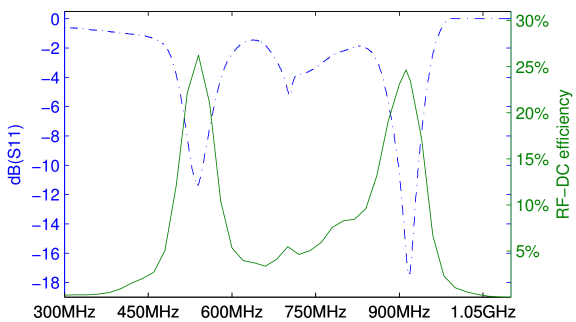



(a)

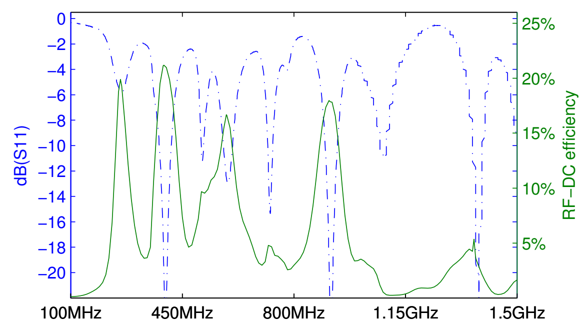



(b)

Fig. 8. Two multiband harvester prototypes were constructed: A 2-band harvester (a), and a 5-band harvester with diode summation network (b). The 5-band prototype measures 1.5 by 1.2 inches.




(a)




(b)

Fig. 9. S11 (reflected power at RF port) and RF-DC conversion efficiency over the operating band for both the 2-band harvester (a) and 5-band harvester (b), for a -10 dBm test power and a 100 kΩ load.

## A. Tuning the prototype

Tuning of the prototypes was accomplished by first treating each band independently prior to combining them in parallel. We first shorted the bandpass filter for each band in isolation, and iteratively searched for L-match network values which gave a good match for that band. Once a good match was accomplished with the bandpass filter shorted, we forward computed bandpass filter component values (using Q=1). These filters were installed, and it was verified that the change in input impedance at the trunk node (for each design frequency) with the introduction of the filter was not significant. After performing the above steps for every band in isolation, all bands were installed and the overall behavior of the harvester could be observed. All iterative tuning was done at a test power of -10 dBm.

During the following tests to characterize the performance of the harvester, A 100 kΩ resistive load was placed at the output of the summation network.

## B. Single-tone response

The 2-band and 5-band prototypes were first subjected to a single-tone excitation at a power level of -10 dBm (100 $\mu$W), and the S11 (reflected power) and RF-DC conversion efficiency were measured. These single-tone results are shown in Figures 9(a) and 9(b).

We observe that, in this system, S11 is not a good predictor for RF-DC conversion efficiency. While the minimal S11 and maximal RF-DC efficiency points for the 2-band prototype matched well, the 5-band harvester did not exhibit the same correlation for every band. For instance, there were many spurious dips in the S11 which did not correspond to design frequencies, and for which conversion efficiency was very low. We also note that the peak efficiency decreased when moving from the 2-band to the 5-band system. We hypothesize that both of these effects are due to interaction between adjacent bands in the system, as the quality factor of the isolating bandpass filters was very low.

The fifth band exhibited a very poor RF-DC conversion efficiency, again seemingly in conflict with its very good S11. It is likely that the RF diodes used are not efficient for

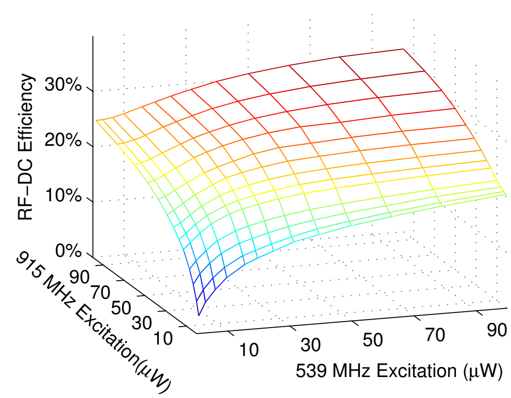



Fig. 10. Measured RF-DC conversion efficiency for the two-band prototype as a function of input power at both design frequencies. A 100 kΩ load was used.

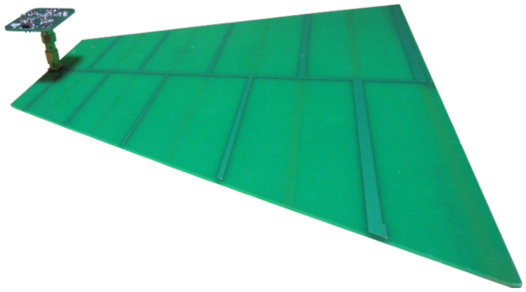


Fig. 11. The 5-band harvester prototype connected to a log-periodic antenna spanning 400-900 MHz.

rectification at this high frequency, and this may account for much of the reduction in efficiency seen in the fifth band.

### C. Multi-excitation response

An experiment was then performed to characterize the multi-band excitation response of the 2-band prototype. The goal of this experiment is to quantify how well the harvester can combine power from multiple bands.

The multi-excitation experiment consists of a two-band excitation produced by combining the output of two RF function generators. This is a highly controllable cabled experiment which can help quantify the effect of multiple excitations on performance, and quantify the effectiveness of the power combination method used. Only the 2-band prototype was subjected to this experiment. Figure 10 illustrates the performance of power combination between bands. Interestingly, the RF-DC conversion efficiency of the entire system increases as more bands are excited.

### D. In the wild

The 5-band harvester was subjected to two scenarios in which "wild" RF energy was present. In the first scenario, it was placed in the field of a UHF RFID reader emitting 30 dBm at 915 MHz into a 6 dBic circularly polarized antenna. At a distance of 5 m from the RFID reader, the harvester was able to produce 2.3 V across a 100 k$\Omega$ load, for a delivered power of 53 $\mu$W.

In the second scenario, the 5-band harvester was placed at a location 4.2 km distant from a TV broadcast tower emitting 1 MW at 539 MHz, and was able to produce 2.5 V across the same 100 k$\Omega$ load for a delivered power of 62.5 $\mu$W. These "wild" scenarios appear to indicate that the antenna-connected harvester appears to work serviceably with single-band excitation from two very different RF sources.

## VI. Conclusion

The multiband harvester presented in this paper provides three distinct benefits: (1) RF source flexibility (2) access to additional power and (3) improved sensitivity. RF source flexibility means that the harvester is able to operate using any subset of several potential source frequencies. The second benefit of multiband harvesting is that it provides access to additional power because the harvester can collect energy from multiple RF sources simultaneously. The third benefit is that multiband harvesting can provide improved sensitivity in circumstances in which no one source provides enough power to operate the device, but several sources in combination do.

RF source flexibility is significant because it enables mobile RF harvesting: the frequency of the strongest RF source is not generally the same in each city; the multiband harvester presented here allows a device to capture power from the strongest sources it encounters. The novel diode summation network presented here is crucial for RF source flexibility. A multiband harvester without our diode summation network would require simultaneous excitation in all or most of its input bands. While such a harvester might provide benefits 2 and 3 (increased total power and increased sensitivity), it would not provide benefit 1. One can imagine providing benefit 1 with an actively tunable harvester design, but the active circuitry would typically cost substantial power, resulting in a system with low net efficiency.

The efficient multiband harvesting presented here can enable mobile RF harvesting, increasing the practicality of ambient RF as a power source. Applied in the context of RFID, this can enable a sensor tag that uses ambient RF power to sense and log data (an application similar to [13]), and then downloads the data when interrogated by an RFID reader.

### A. Future Work

It remains to be proven whether this harvesting topology can in fact scale to be efficient over an arbitrarily large number of bands, and a more rigorous analysis of the system will be needed in order to draw a conclusion on the potential limitations of scaling. However, the simulated and prototype results appear to mostly support the conclusion that it is possible to scale the system to a large number of bands while maintaining reasonable efficiency levels.

Integration lends itself to the high component count and modeling complexity of high band count multiband harvesters. An integrated multiband system with a single antenna port could become a universal RF energy harvesting solution, able to be used in a plug-n-play fashion with a wide variety of antennas and across a wide variety of target frequencies.


## VII. Acknowledgements

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