Active Power Summation for Efficient Multiband RF Energy Harvesting

Aaron N. Parks[1], Joshua R. Smith[2,1]

[1]Electrical Engineering Department and [2]Computer Science and Engineering Department

University of Washington, Seattle, USA-98195

{anparks,jrs}@cs.washington.edu

***Abstract*—Radio frequency scavenging power supplies targeting ambient and/or intentional sources of energy present a reliability challenge when faced with single-source fading (both geographic and small scale), and this is an impediment to their practical adoption. Recent work has described simultaneous harvesting of power from multiple spectrally separated bands as a method to mitigate single-source fading. The method used for summation of DC output power from each band rectifier is critical in determining efficiency of the multiband harvester. Existing work explores a diode network topology for summation of power, but this network doesn't always provide a benefit over a naive implementation of power summation. This paper characterizes the costs and benefits of existing power summation topologies, and introduces a new intelligent switching method for summation which generally exceeds the performance of prior methods.**

I. Introduction

Ambient RF harvesting power supplies promise to enable battery-free or energy-neutral operation for future devices spanning the entire spectrum of consumer and industrial electronics. The feasibility of powering sensing, computation, and communication devices using ambient radio frequency (RF) energy has been a topic of academic research in recent years[1], [2], [3]. However, most prior work in ambient RF harvesting has focused on single ambient sources of energy, such as a particular television channel[1], [3]. This highly targeted RF harvesting has the downside of being highly influenced by large scale fading (geographical fading) and small scale fading (multipath interference) for the source targeted. For instance, a harvester targeting a television channel will only work in locations near where that channel is being broadcast.

To address the issue of single-source fading, some work has proposed use of multiband harvesting in which multiple frequency bands are targeted simultaneously. Some multiband harvesting topologies make use of multiple antennas or antennas with multiple ports[4], while others divide power from a single wideband antenna into multiple bands and match to multiple rectifiers[5], [6]. One common aspect across multiband harvester topologies is that power from each band is typically combined at DC, after rectification takes place.

This leads to the key question of how best to combine power from multiple harvesters in a multiband harvesting network. In [5], a method for DC combination of power using a network of diodes is presented. However, in some cases the technique does not provide an efficiency improvement, and it is not clear when a benefit will be experienced. This paper will discuss the design space around DC combination of power from multiple bands in a multiband RF harvester, and will characterize three approaches to power summation, with the goal of identifying the conditions under which each technique is most effective.

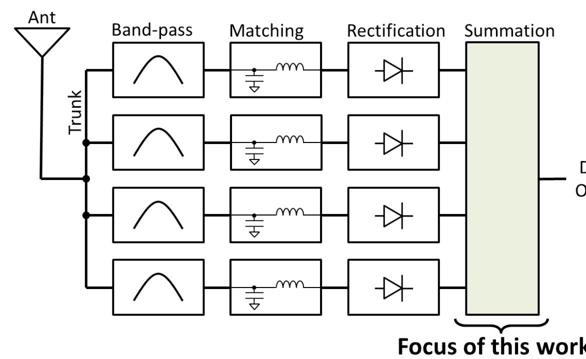


Fig. 1: The multiband RF harvester introduced in [5] scavenges energy from multiple sources simultaneously to mitigate the effects of single-source fading and thereby produce a more reliable and robust power supply. Efficient summation of DC output power from each band harvester is the challenge addressed in this work.

II. Designing for efficient power summation

A naive approach to power summation is to combine band DC outputs serially or in parallel. Serial summation topologies give the best voltage sensitivity, which is key when considering operating requirements of the load; a typical load will need significant developed voltage to operate. Even a DC-DC conversion stage will typically require hundreds of millivolts in order to bootstrap and begin moving charge[3].

In [5], the authors describe why a simple serial combination of RF harvesters hinders current flow when some bands are not excited. This turns out to be due to the impact of the unexcited bands' RF-DC conversion diodes; at low or zero excitation power the diodes cease to be a source of voltage and begin developing a voltage drop, therefore impeding the flow of current from serially-connected excited bands. Summation topologies which overcome this must allow current to divert *around* unexcited bands by providing a path of far lesser resistance. In effect, inactive bands must be shorted by some switching method.

Because it's difficult to produce semiconductor switches which are normally-closed with no supply voltage present, a

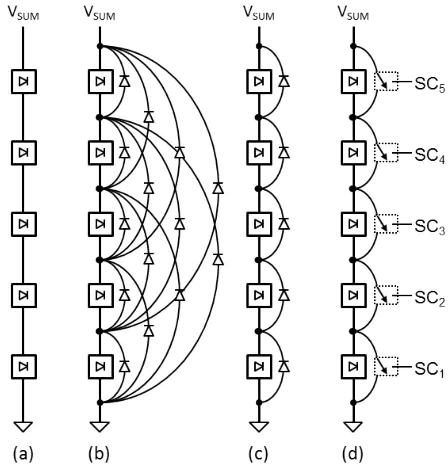


Fig. 2: Four methods of serially combining power from multiple bands in a multiband RF harvester: (a) is the naive implementation involving simple serial combination. (b) adds implements the full diode summation network described in[5]. (c) simplifies the summation network to only first-tier shortcut diodes. (d) intelligently bypasses unexcited harvesters with normally-open switches.

harvester which is capable of cold-starting (starting with all circuit nodes at zero volts) cannot have normally-closed connections. This reinforces the decision to use a serial topology; normally-open switches can be used to short inactive bands and will also behave as open switches during a cold-start.

There are multiple ways to address the serial combination of bands which include unexcited bands. The following three methods for summation will be discussed in this work:

A. Full shortcut diode network

The switches mentioned above for shorting unexcited bands can in fact be implemented by diodes. Shorting unexcited harvester bands simply requires an anti-parallel-connected diode which becomes forward-biased when the band output voltage is small and when other bands become active. Prior work[5] described a network of diodes for summation of power from multiple serially-connected bands, which ensures that each excited band is separated from others by at most one diode drop. This network is shown in Figure 2 (b) and will be the first topology characterized.

B. Simplified shortcut diode network

This work proposes a simplification of the full diode network, in which only the first level of shortcut diodes is implemented. This has the benefit of lower complexity and potentially lower sum leakage current in large band count multiband harvesters. This topology is shown in Figure 2 (c).

C. Intelligent shortcut switching summation network

The final topology proposed in this work replaces diode switching with controlled analog switches, which are managed by a logic system. The switches themselves are pictured in Figure 2 (d). A flow diagram for a logic system to control those switches is given in Figure 3.

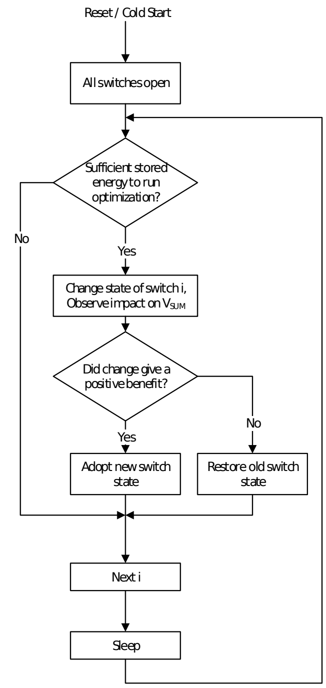


Fig. 3: Control logic flowchart for implementing the intelligent summation network. Each loop iteration involves testing and updating only one switch, as this requires minimal energy and therefore a smaller reservoir of stored charge.

III. Simulated results

Models of each of the three summation topologies were constructed. A 5-band harvester model was used as a source in a simulation testbench. The goal of modeling is to characterize the summation benefit of each method over a naive serial combination of DC harvester outputs as a function of the excitation state of the 5-band harvester.

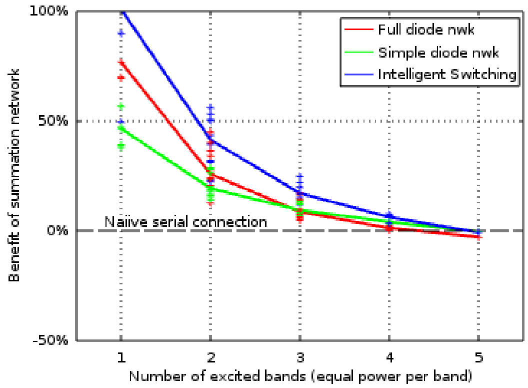
A. Test setup: Multiexcitation testing

Two fixed-resistance loads were used in each test scenario, 10 kΩ and 100 kΩ, and represent typical μW-scale loads experienced in an energy harvesting device[2]. A load capacitance of 10 nF was used. Two excitation power levels were used in each test scenario, -10 dBm and -20 dBm. In the multiexcitation tests, each excited band for a particular test was subjected to this excitation power and the other frequency bands were left unexcited. Every possible permutation of excited bands was tested for each data set. For each data point in each set, a transient simulation was allowed to run until a stable output voltage was reached, and the power across the load was then computed.

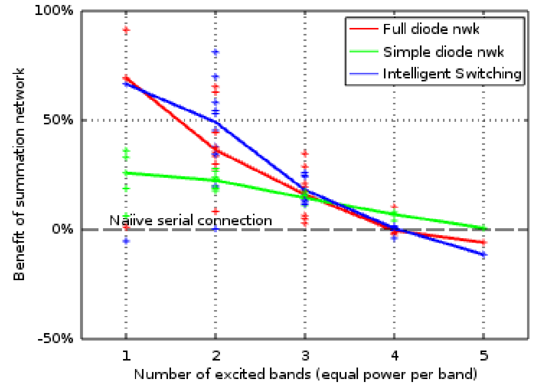
Low forward voltage and low reverse saturation current both must be achieved for summation network diodes to

TABLE I: SPICE model for HSMS-282 diode used in serial summation

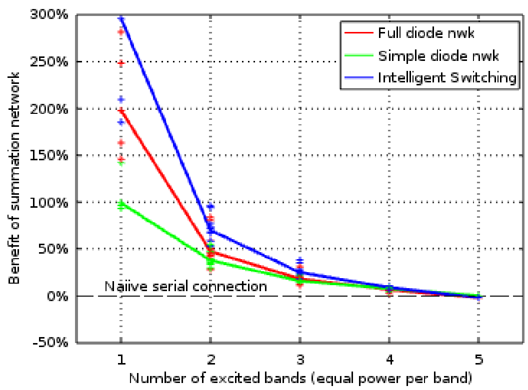
```
D(IS=4.8E-8, CJO=0.649E-12, VJ=.56,
   BV=26.7,    IBV=10E-4,      EG=0.69,
   N=1.067,    RS=7.8,         XTI=2,
   M=0.5)
```



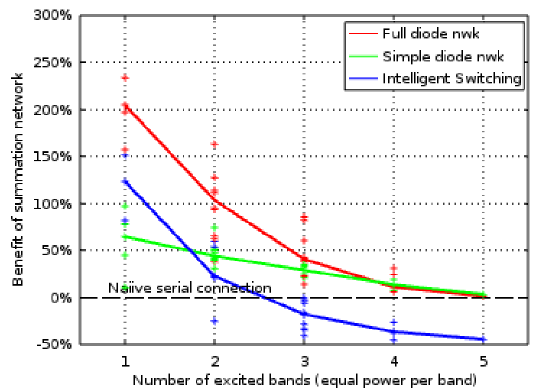
(a) Benefit of three summation networks with $R_{LOAD} = 100$ kΩ, $P_{RF} = -10$dBm per band.



(b) Benefit of three summation networks with $R_{LOAD} = 100$ kΩ, $P_{RF} = -20$dBm per band.



(c) Benefit of three summation networks with $R_{LOAD} = 10$ kΩ, $P_{RF} = -10$dBm per band.



(d) Benefit of three summation networks with $R_{LOAD} = 10$ kΩ, $P_{RF} = -20$dBm per band.

have a positive benefit. In all tests the HSMS-282 Schottky barrier diodes were used for summation as they have very low advertised forward voltage while maintaining low reverse saturation current. The parameters of the diode models used in the diode summation network are given in Table I.

In the modeled intelligent switching network, bands left unexcited were bypassed by switches. The switch model used a 50 Ω 'on' resistance and a 10 MΩ 'off' resistance, conservatively chosen values for low power analog switches such as the ADG802 operating at low voltages[7]. Switch power consumption for the ADG802 is under 10 nW per device. To estimate the overhead of the control logic, a TI MSP430G2553 microcontroller power consumption in low power mode (LPM3, with a crystal oscillator active) was assumed[8][1]. The total power consumption of switches and control logic is just under 1 μW, and all results involving intelligent switching reflect this overhead.

B. Analysis of results

Figures 4a, 4b, 4c, and 4d illustrate multiband harvester performance using each of the three summation methods from Figure 2 for two power levels and two values of load resistance. For each permutation of excited harvester bands, total power delivered to the specified load resistance was determined for each of the three summation topologies of Figures 2 (b),(c), and (d), and for the naive serial connection of Figure 2 (a). The solid line in each plot shows the median benefit of the summation network as a fractional power increase over the naive serial implementation, which is shown by the dotted black line.

It is observed that the diode summation network of Figure 2 (b) generally provides a benefit excepting the case in which all five bands are excited. The simple diode summation network of Figure 2 (c) also reliably provides a benefit, but in general is less beneficial than the full diode summation network.

The intelligent switching summation network, however, provides a strong benefit at higher input power (Figure 4a and 4c) but is less advantageous, and even becomes an impediment, as excitation power drops (especially Figure 4d). This decrease in efficacy with very low excitation power is a symptom of the power draw of the logic system for the intelligent switching network, and therefore is highly dependent on specific implementation.

IV. Conclusion

Three methods for summation of power in a multiband RF harvester were characterized. The design of a novel intelligent switching summation network was introduced and the projected performance of this network was characterized

[1] Though the microcontroller cannot actively control switches in low power mode, it can choose to spend the overwhelming majority of its time in this mode and therefore it's an acceptable approximation of power consumption.

through simulation. The intelligent switching network provides a significant benefit over prior art in most cases, excepting very low excitation power.

V. Acknowledgements

This work was supported in part by NSF award number CNS 1305072.

References

[1] A. Sample and J. Smith, “Experimental results with two wireless power transfer systems,” in *Radio and Wireless Symposium, 2009. RWS ’09. IEEE*, pp. 16–18, 2009.

[2] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, “Ambient backscatter: wireless communication out of thin air,” in *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, pp. 39–50, ACM, 2013.

[3] A. Parks, A. Sample, Y. Zhao, and J. Smith, “A wireless sensing platform utilizing ambient rf energy,” in *Radio and Wireless Symposium (RWS), 2013 IEEE*, pp. 331–333, 2013.

[4] S. Keyrouz, H. Visser, and A. Tijhuis, “Multi-band simultaneous radio frequency energy harvesting,” in *Antennas and Propagation (EuCAP), 2013 7th European Conference on*, pp. 3058–3061, 2013.

[5] A. Parks and J. Smith, “Sifting through the airwaves: Efficient and scalable multiband rf harvesting,” in *RFID (IEEE RFID), 2014 IEEE International Conference on*, pp. 74–81, April 2014.

[6] D. Pavone, A. Buonanno, M. D’Urso, and F. G. Della Corte, “Design considerations for radio frequency energy harvesting devices,” *Progress In Electromagnetics Research B*, vol. 45, pp. 19–35, 2012.

[7] “Adg801/802 datasheet,”

[8] “Msp430g2x53 datasheet,”