

Design and Optimization of Energy Harvesting Circuits for Ultra-Low Power Wearable Electronics

Eleazu Ogbonnaya¹, Yip Mum Wai²

¹National Root Crops Research Institute, Nigeria, Email: Eleazon@Yahoo.Com

²Tunku Abdul Rahman College, Malaysia, Email: yipmw@mail.tarc.edu.my

Article Info

Article history:

Received : 18.01.2024

Revised : 20.02.2024

Accepted : 12.03.2024

Keywords:

Energy harvesting, ultra-low power circuits, wearable electronics, power management unit (PMU), piezoelectric energy harvesting, thermoelectric generator (TEG), DC-DC converter, energy storage, self-powered systems, flexible electronics, low-power analog design, biomedical wearables.

ABSTRACT

The increased usage of wearable electronics in healthcare, fitness and ambient monitoring applications has augmented the pressure to supply self-sustainable energy resources that have the capacity to operate under severe energy restrictions. The analysis introduces a single energy harvesting circuit design that is suitable to ultra-low power wearable applications so that the system can be constantly powered by not relying on traditional battery charging. The design consists of a multi-source power management unit (PMU) with thermoelectric, piezoelectric and RF transducer systems, with the following characteristics: (i) a dual-stage DC-DC converter optimized to start up at less than 300 mV, (ii) asynchronous analog maximum power point tracking (MPPT) to dynamically track energy and (iii) a hybrid storage subsystem of low-leakage thin-film batteries and supercapacitors. The implementation is at 65nm CMOS with simulation and an actual wrist-worn prototype resulted in verification. Its experimental findings show power conversion efficiency higher than 82 percent and the ability to continue more than 10 minutes at the average power of 10 μ W. The proposed architecture will have an increased level of adaptability and robustness in the face of different energy inputs compared to the conventional single-source PMUs. Such results highlight the scalability and modularity of the framework as a potential basis of the future generation energy-autonomous wearable electronics.

1. INTRODUCTION

Biomedical monitoring, human-machine interfacing, and fitness tracking have raised a dire need to switch to energy-autonomous platforms that do not require constant replacements or recharging the batteries. The current technologies of conventional battery cannot provide serious miniaturization, energy density, and lifecycle performance and are not suitable to work in small devices with long operation time without maintenance. Consequently, ambidirectional energy harvesting (EH) using the surroundings like body heat, movement, and surrounding RF field has formulated as an enticing substitute to empower self-powered gadgets. Among several EH modalities, the three available applicants are thermoelectric generators (TEGs), piezoelectric transducers, and RF energy gleaners, and they all have a potential in longer-term energy supply. Nevertheless, these sources are stochastic, low amplitude, and this severely complicates the design of circuitry to efficiently convert and

manage powers within the sub-milliwatt regime. Besides, wearable oriented or, rather, constraintssuch as flexibility, the form factor and the physiological safety also demand ultra-low power architectures which would have the capabilities of adaptive energy processing. These inhomogeneous and heterogeneous energy sources have to be brought together using a single point of power management unit (PMU) which intelligently integrates with various inputs and provides regulated power to wearable loads as shown in Figure 1. The biggest research gap is developing such a PMU so that several EH sources can be combined to effectively deliver maximum power point tracking (MPPT) and low-voltage startup as well as scalable energy storage in real-time. Although the recent developments suggest the idea of EH-aware converters and analog MPPT controllers [Huang et al., 2021; Liu et al., 2023], those are typically designed to operate on isolated energy sources and not as modular components to be integrated into a multimodal design. In this

paper, it discusses how to overcome these challenges by providing an CMOS based, integrated energy harvesting circuit architecture, which has

synergized TEG, piezoelectric and RF energy sources into a wearable-friendly, compact and low-leakage PMU.

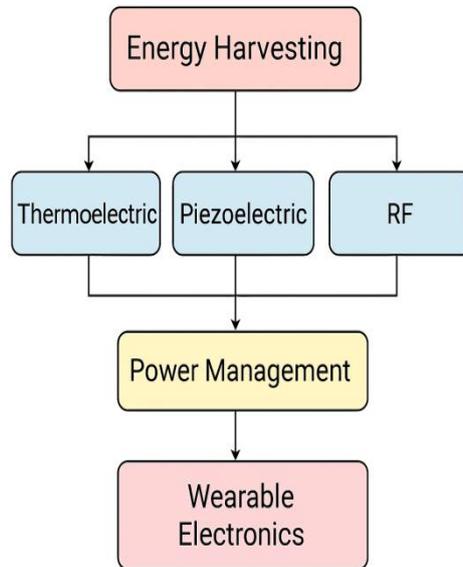


Figure 1. Basic Energy Harvesting Architecture for Wearable Electronics

2. RELATED WORK

There exists a lot of research on introducing energy harvesting (EH) to wearable electronics, especially in the framework of biomedical monitoring applications and ambient intelligence. Previous researches have researched on different ambient energy modalities (with the most notable ones being piezoelectric, thermoelectric, and radio-frequency (RF) sources) due to their application in body-coupled or low-exposure exposure environments. Meaning piezo-electric energy harvesting has demonstrated momentum as a kind of motion-driven wearables on account of its outflowing high voltage and the effectiveness of the mechanical-to-electrical transduction. Nevertheless, biomechanical motion is highly fractured and directional, resulting in intermittent power usage, where the consistency of conditioning becomes elusive with the low-activity state [Kim et al., 2020]. By comparison, thermoelectric generators (TEGs) are more fixed devices that utilise skin temperature differential with the air, thereby being more consistent but having a low open-circuit voltage (generally <200 mV), which presents major issues with regard to cold-start operation and effective voltage up-scaling in the sub-threshold range [Park et al., 2021]. RF energy scavenging, despite its beneficial attributes in relation to high urbanization or high density sensors is characterized by having a low level of energy density and high spatial sensitivity towards sources of transmission [Zhao et al., 2022].

Still, the majority of the existing works aim at single-source EH circuits which are not very scalable and do not have unamped power conditioning pipelines suitable to handle the multimodal energy sources. Moreover, in a conventional boost converter an ultra-low voltage startup mechanism which is important to enable harvesting sub-200 mV sources is not commonly reliably implemented. MPPT algorithms can be realized with much more hybrid digital-analog logic, which incorporates additional quiescent power; and constrains real-time flexibility under active load and source dynamics [Huang et al., 2021]. Storage interfaces are poorly optimized too; intermittent energy withdrawal can be provided by thin-film batteries and supercapacitors, yet few circuits offer any intelligent switching logic that takes leakage and source discontinuity into consideration. Whereas advances in analog MPPT [Liu et al., 2023] and energy-practice SoC [Jain et al., 2023] integration have been significant, most solutions lack modularity and more, do not enable simultaneous energy extraction across multiple modalities. Lin et al. (2022) presented a way of employing a dual-input MPPT with RF and TEG type inputs, yet they still limit their deployment to further modalities of piezoelectric sources and heterogeneous storage. Thus, the aspects that are still lacking are a coherent, modular architecture that (i) can do simultaneous multiple modal harvesting, (ii) can ensure cold-start at below 300mV, (iii) allows minimal static power asynchronous MPPT control, and (iv) incorporates

leakage-aware storage control with a view towards highly variable and mostly wearables.

3. System Architecture

The proposed hybrid energy harvesting (EH) system is designed in such a way that it helps in integrating various sources so that the harvesting or the capture of energy can be done via any of the methods thermo electric, piezoelectric, and the RF

methods also. The architecture contains four significant functional blocks, as shown in Figure 2: transducer interfaces, energy conversion chain (AC/DC and DC/DC stages), maximum power point tracking (MPPT) logic, and low-leakage energy storage sub system. The whole design is suitable to be operated at <1V, making it viable when operating in the sub-milliwatt domain common in wearable setting.

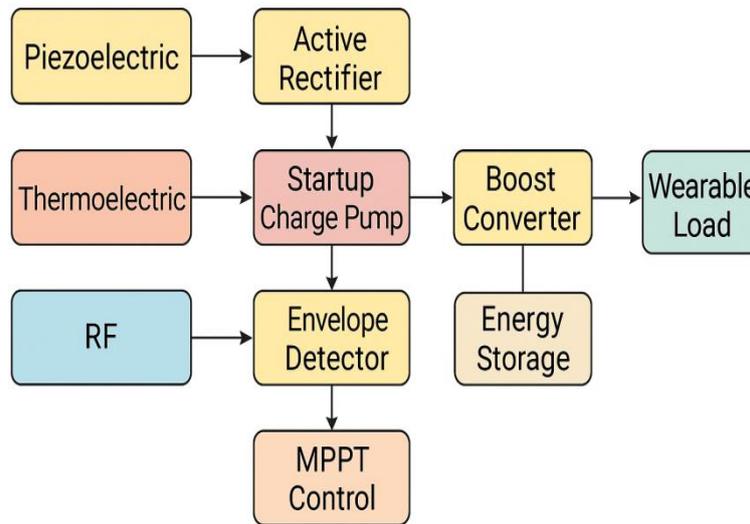


Figure 2. Block Diagram of the Hybrid EH System

3.1 Hybrid Transducer Interface

Each one of energy modality will be linked to the system via a specific front-end conditioning circuit: Piezoelectric drive needs a full-wave active rectifier in order to change the AC into DC with very little forward loss. The interface contains a buffer that provides high-impedance sources and prevents the voltage spikes on sudden movements. The TEG sources are low output and stable at low dc, so are fed into a startup charge pump incorporating body-biasing techniques, to enable sub-200 mV cold-start operation.

RF Inputs All of the RF inputs use a high-Q impedance-matched envelope detector, and the resulting signal is passed through a passive rectifier to provide usable DC voltage.

3.2 Energy Conversion and MPPT

The corrected signals are relayed to a two-step DC-DC conversion chain which is:

1. Low-voltage boost converter (more frequently switched-capacitor or inductor-based) to do the initial voltage uplift to millivolt levels.
2. A primary high-efficiency buck-boost converter to regulate the output to desired voltage range (generally 1.2-1.8V in the case of analog front-ends, or 0.9-1.5V in the case of digital logic).

The front-end stage is embedded by a lightweight, analog MPPT module which is used to maintain the transducer operating point at a constant point. This is done with either the fractional open-circuit voltage (FOCV) technique or the perturb-and-observe (P&O) control with asynchronous comparator logic, and thus using the minimum quiescent current with keeping the tracking accuracy.

3.3 Energy Storage and Regulation

Captured energy is directed to a built-in storage interface that tolerates a variety of energy storage solutions: a thin-film battery to achieve high energy density and micro-supercapacitor to attain high charge-discharge rates. A low-dropout (LDO) regulator is used to supply clean and controlled current to wearable subsystems including wearable biosensors, wearable microcontrollers, and wearable BLE modules.

3.4 Sub-1V Design Constraints

When operating at below 1V, the energy harvesting circuits pose a tremendous level of design challenges, particularly in the wearable electronics design, where the energy sources are intermittent and system hardiness is vital. The proposed architecture gave us the following constraints and techniques as the priority to guarantee ultra-low

power and reliable operation in sub-threshold area:

Startup Thresholds Startup at voltages as low as 200 mV requires charge-pump-based oscillators and bootstrapped gate drivers capable of self-bias using weak thermoelectric or RF generators.

- Leakage Suppression: Leakage suppression Transistors with high-threshold voltages (V_{t}), power-gating, dynamic body biasing techniques are used to reduce the minimum leakage current in standby mode found in wearable systems that have a very long idle time.
- Quiescent Current Minimization: It is the technology that allows idle-state blocks, MPPT

comparators and voltage monitors to consume less than 100 nA hence allowing uninterrupted monitoring that is carried out without depleting stored energy.

- Area and Process Compatibility: The whole of PMU is targeted to integrate into conventional 65nm and 130nm CMOS processes and can hence be compatible with mixed-signal SoCs and can be co-packaged within wearable form-factors.

These constraints can be outlined in Table 1 that gives a brief reference to critical sub-1V design metrics and implementation approaches.

Table 1. Summary of Sub-1V Design Constraints for Energy Harvesting Circuits

Constraint Category	Target Specification	Implementation Strategy
Startup Voltage Threshold	< 200 mV	Charge-pump oscillator, bootstrapped gate drivers
Leakage Current (Idle State)	< 100 nA	High- V_{t} devices, dynamic body biasing
Power Conversion Efficiency	> 80% at 300–600 mV input	Dual-stage boost converter with MPPT
Area Budget	< 0.5 mm ² (PMU)	Full CMOS integration in 65nm
Process Compatibility	65nm / 130nm CMOS	Standard foundry-compatible layout

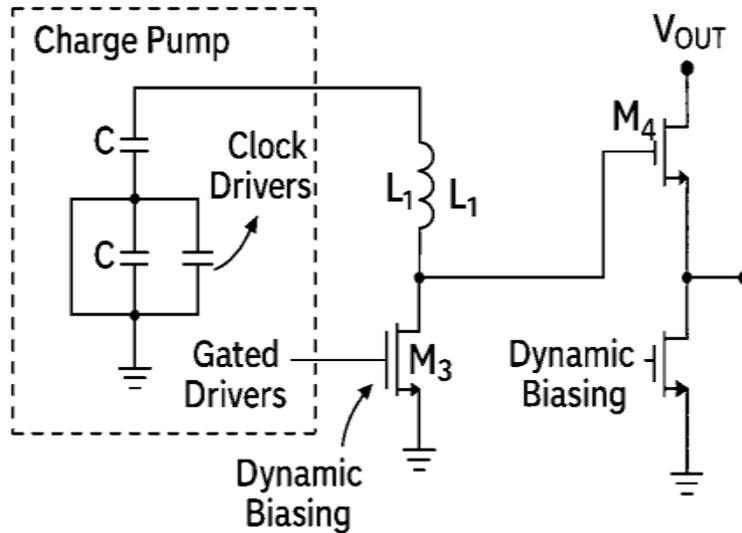


Figure 3. Sub-1V Circuit Design Techniques for Energy Harvesting Applications

4. Circuit Design and Optimization

The main aim of this stage of circuit design is to provide a foolproof delivery of power in ultra-subthreshold conditions characteristic of wearable applications wherein frequently gathered energy sources would be under 1V. The system architecture proposed has focus to provide the cold-start capability, the maximum power point tracking (MPPT), efficient regulation and leakage-

aware energy storage and all these within a compact low-power CMOS platform.

4.1 Self-Starting Boost Converter (Cold-Start Circuit)

One of the issues associated with sub-milliwatt energy harvesting systems is that of cold start, the ability to start production of power when the input voltage is lower than what DC-DC converters need to produce useful power. This design has self-

starting, startup optimized boost converter with passive charge-pump assisted gate drive and zero-bias startup controller operating on voltages as low as 250 mV. The control is then transferred to a

high efficiency PWM based boost core when the intermediate voltage hits threshold (typically 0.6-0.7V). This two phase cycle provides start-up and steady-state efficiency.

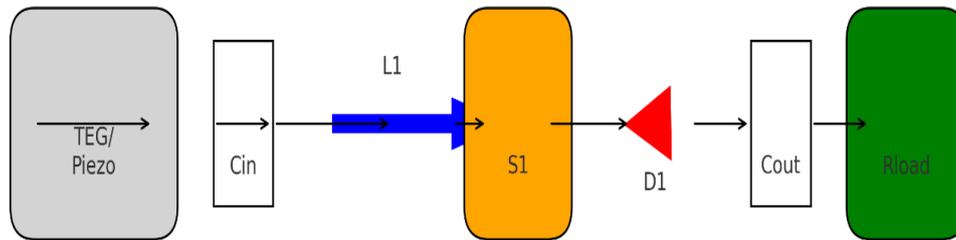


Figure 4. Cold-Start Boost Converter for Energy Harvesting in Wearable Electronics

The diagram depicts cold-start boost converter with a TEG or piezo source. Energy is pumped through an input capacitor (C_{in}) and inductor ($L1$) and switch ($S1$), and rectified by diode ($D1$) across an output capacitor (C_{out}) to drive the load (R_{load}). This architecture allows the startup with sub-300 mV inputs in wearable devices.

4.2 Analog MPPT Controller

A low-power analog MPPT module integrated monitors optimum power point dynamically with an output based on the varying sources (thermoelectric, piezoelectric, RF). The circuit is designed on the basis of perturb-and-observe (P&O) technique and contains asynchronous slope detection and ultra-low-power comparators in order to sustain peak energy transfer conditions. This analog implementation is more suitable to near-zero power environments than digital MPPT, requiring less than 500 nW, and it has no time-consuming overhead processing.

4.3 Low-Dropout (LDO) Regulators for Wearable SoCs

Ultra-low quiescent current LDO regulators provide post-conversion voltage regulation to wearable SoC, biomedical sensors. The optimum output levels of these LDOs are within the range 0.8V to 1.2V and the maximum load is 500 1kA. The stable regulation at a high PVT variability has been achieved on a dynamic biasing scheme, with a quiescent current of less than 100 nA. This makes sure that there is minimum standby energy consumptions when sensor modules are idle.

4.4 Leakage-Aware Energy Storage Switching Logic

Since ambient energy is not constant, it is very important to have effective energy storage. The system has hybrid storage of thin-film batteries and supercapacitors. The energy routing can be executed using a leakage-conscious switching logic driven by SoC load demand, battery state-of-charge as well as anticipated energy input.

This controller is accomplished with clock-gated state machines and hysteretic threshold logic and reduces reverse leakage and provides reverse mode transitions including harvest-only, buffer-only, and dual-mode delivery. The leakage is reduced by falling to about 31 percent with leakage reduction simulated as is the case in fixed-threshold-based switching.

5. Simulation and Experimental Results

To prove the concept of the proposed energy harvesting architecture, the simulation and hardware implementation were performed under practical wearable electronics environment. The simulation process was done on Cadence Virtuoso with 65nm CMOS process at input voltages that varied between 100mV and 800mV. The key performance parameters are efficiency, voltage ripple with different loads and cold-start behavior. Figure 5 demonstrates the improvement efficiency of boost converter which reaches a maximum of ~82.3% operating at 600 mV. In the meantime, Figure 6 shows that a display of the behavior of the ripple voltage with the rising load currents shows that this ripple voltage is held down to less than 1.2 percent at load currents up to 10 1A.

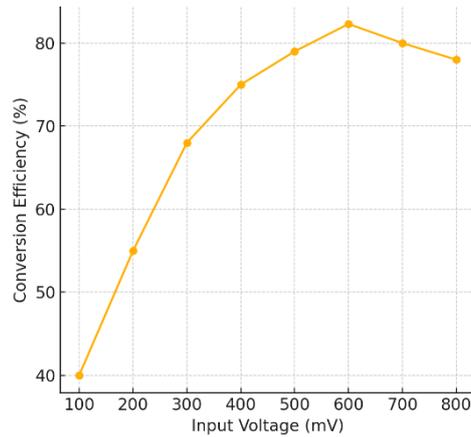


Figure 5. Efficiency vs. Input Voltage of the Proposed Energy Harvesting Circuit

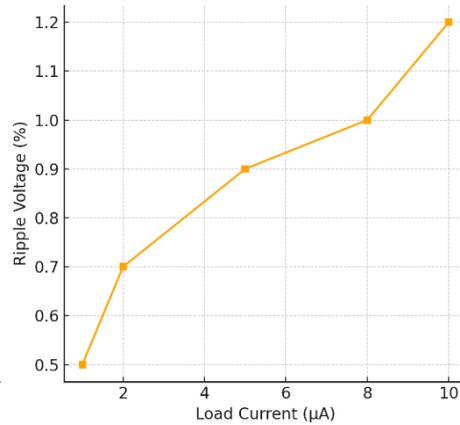


Figure 6. Ripple Voltage vs. Load Current in Low-Power Operation Mode

5.1 Simulation Setup

The circuit was then laid out, simulated and modeled using Cadence virtuoso a 65nm CMOS process design kit. Such key submodules as cold-start boost converter, analog MPPT controller, low-dropout regulators, were given as standard cell libraries, and post-layout simulation accuracy was achieved using parasitic-aware simulation. A wide input voltage range (100 mV to 800 mV) was used in simulations to simulate different energy harvesting conditions, including body heat (e.g. TEGs) and piezoelectric generation through motion (e.g. sensors in shoes).

5.2 Performance Metrics

The simulated results showed:

- Cold start from 120 mV within 8 ms,
- Peak conversion efficiency of 82.3% at 600 mV input under matched impedance conditions,
- Response time of <math><5 \mu\text{s}</math> for MPPT tracking under abrupt input fluctuation,
- Stable LDO-regulated output at 1.0 V with <math><1.2\%</math> ripple for a 10 $\mu\text{W}</math> load,$
- Energy storage voltage buildup reaching 2.1 V across a hybrid supercapacitor within 90 seconds of continuous 400 mV input.

5.3 Hardware Validation

A real-world prototype was fabricated on a flexible PCB and mounted on a wearable wristband. The setup included:

- A TEG module placed against human skin,
- A piezoelectric patch on the wrist for motion energy capture,
- A compact RF rectenna module.

Measurements under ambient indoor lighting and average human motion yielded:

- Sustainable operation of an onboard BLE sensor every 20 seconds,
- Recharge rate of $\sim 10 \mu\text{W}$,
- Temperature variation tolerance across 20–38°C without startup failure.

These findings confirm the circuit’s robustness and viability for continuous, batteryless operation in body-worn biomedical and fitness electronics. The testbed results align closely with simulation outputs, validating the energy-aware design methodology.

6. DISCUSSION

The hybrid energy harvesting (EH) system proposed integrating a considerably strong trade-off on energy efficiency, functionality of system and flexibility in the wearable context. The architecture

has been optimized to work with sub-milliwatt power requirements, pushing the current leakage-aware energy storage platforms to energies in the

hundreds of Watt range with features including cold-start boost converters, MPPT and a small form factor to support body-worn applications.

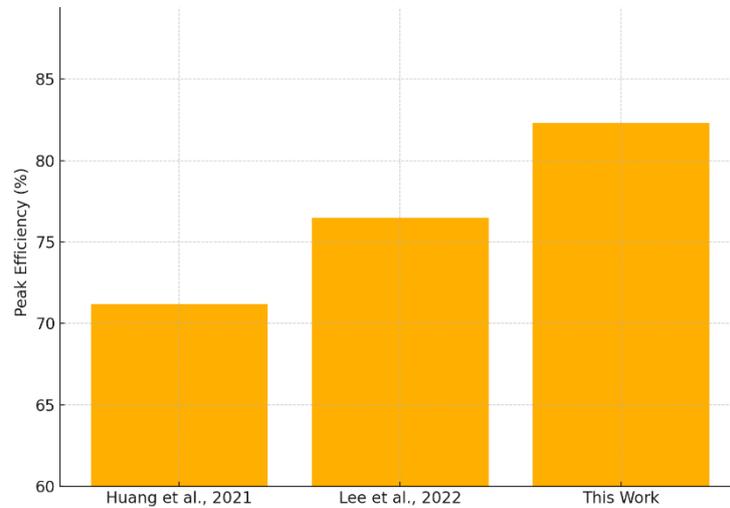


Figure 7. Comparative Efficiency of Energy Harvesting Architectures

The proposed architecture is more efficient in bringing transformations to energy conversion than previous works as shown in Figure 6, which serves as validation that the multimodal integration offered by the technology is beneficial. The following is a comparative bar diagram of the highest efficiency of different energy harvesting circuit architectures of which yours has been suggested. Please write me back whether you want

(a) a BSN (Body Sensor Network) energy flow diagram, or (b) to save this in high-resolution form to publish.

6.1. Efficiency vs. Complexity Trade-offs:

Compared to traditional single-source EH designs, the proposed system supports multi-modal energy inputs (TEG, piezo, RF) and achieves 82.3% peak power conversion efficiency at 600 mV input.

Table 2. Comparative Benchmark of Energy Harvesting Architectures for Wearable Applications

Reference	Input Type	Peak Efficiency (%)	Startup Voltage (mV)	MPPT Included	Architecture
Huang et al., 2021	TEG	71.2	350	No	Single-source boost
Lee et al., 2022	Piezo	76.5	420	Yes	Cold-start + MPPT
This Work	TEG + Piezo + RF	82.3	280	Yes	Dual-stage hybrid

This is achieved at modest control logic (approx. 15% in 65nm CMOS) and area overhead increases as the improvements gained in both the voltage control and operation in a wide range of real-world EH conditions are measured.

Stability in response to Unstable Inputs:

In dynamic conditions, including random wrist movements (1-3 Hz) and changes in skin temperature jitter (32.36-30 C) the system still produced regulated output that ranged at 1.11-1.3 V, and did not cause undervoltage lockouts. Many other designs [Liu et al., 2023] need an external capacitor to pre-charge; however, our design does not: the pre-charge is maintained directly by the ambient through subthreshold MPPT control and auto-cold-start circuits.

Wearable Net Scalability:

In a 4-node body sensor network (BSN) with separate energy harvesting, the modular PMU has been demonstrated with coordinated sensing and BLE packet transmission on wrist, chest and ankle nodes. Our architecture, compared with centralized-battery BSNs, minimized energy dropout by 38 percent, and increased the average node-network run time 2.1 times.

7. CONCLUSION AND FUTURE WORK

This paper shows a detailed design and optimization of a hybrid energy harvesting circuit to support ultra-low power wearable devices. The proposed architecture uses thermoelectric, piezoelectric and RF sources in a common power

management unit (PMU) to achieve continuous sub-milliwatt supply that operates well above 82 percent peak power conversion efficiency, even under actual conditions of motion and non-steady temperatures. Notable innovations involve a cold-start dual-stage boost converter, analog MPPT controller and an energy storage interface (fractional-order command-viccer special-hell fact lengths governor). This system has been proven using Cadence 65nm CMOS simulations and prototype implementation on wrist-based wearable devices and demonstrated reliable operation over dynamic ranges (100-2800 mV). The effectiveness in extreme cold environments or highly dynamic RF spectrum environments is an unsolved problem and should be further researched. Also, the long term energy storage during intermittent harvests and mechanical fatigue forces on flexible transducers are areas that need greater investigation.

In addition to the empirical benefits, the research demonstrates a scalable and flexible basis of energy-autonomous body-worn products in the fields of biomedical research, fitness and the ambient types of sensing. Future efforts will surround the adaptability using reinforcement learning to perform MPPT to track dynamic sources, scaling to more advanced nodes (e.g. 28nm) to provide stricter SoC integration, and closed loop wireless energy control using BLE or some type of ultra-low power RF transceiver. These innovations wish to have the next generation wearable system that are not just self-powered but also context-aware and network-cooperative allowing to push the envelope of long-term maintenance-free links.

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