Toward Battery-Free Wearable Devices: The Synergy between Two Feet

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Recent years have witnessed the prevalence of wearable devices. Wearable devices are intelligent and multi-functional, but they rely heavily on batteries. This greatly limits their application scope, where replacement of battery or recharging is challenging or inconvenient. We note that wearable devices have the opportunity to harvest energy from human motion, as they are worn by the users as long as being functioning. In this article, we propose a battery-free sensing platform for wearable devices in the form factor of shoes. It harvests the kinetic energy from walking or running to supply devices with power for sensing, processing, and wireless communication, covering all the functionalities of commercial wearable devices. We achieve this goal by enabling the whole system running on the harvested energy from two feet. Each foot performs separate tasks and two feet are coordinated by ambient backscatter communication. We instantiate this idea by building a prototype, containing energy harvesting insoles, power management circuits, and ambient backscatter module. Evaluation results demonstrate that the system can wake up shortly after several seconds' walk and have sufficient Bluetooth throughput for supporting many applications. We believe that our framework can stir a lot of useful applications that were infeasible previously.

CCS Concepts: • **Computer systems organization → Embedded systems**; *Sensors and actuators*;

Additional Key Words and Phrases: Battery-free, energy harvesting, backscatter communication

ACM Reference format:
Qianyi Huang, Yan Mei, Wei Wang, and Qian Zhang. 2018. Toward Battery-Free Wearable Devices: The Synergy between Two Feet. *ACM Trans. Cyber-Phys. Syst.* 2, 3, Article 20 (June 2018), 18 pages.
https://doi.org/10.1145/3185503

1 INTRODUCTION

Wearable devices are penetrating into our daily lives. As devices of different form factors become available on the market, e.g., smart glasses, wristbands [20], and rings [21], a user may wear a number of on-body devices to cover different functionalities. For example, in addition to a smartphone, a user would also wear a pair of smart glasses for life logging, a wristband for activity monitoring, and a pair of smart shoes for gait analysis and diagnosis. If every on-body device needed to be recharged frequently, it would be very inconvenient. If these devices would be battery-free, it

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This work was supported in part by the RGC under Contract CERG 16212714, 16203215, Contract ITS/143/16FP-A, Contract R8015, and in part by the Guangdong Natural Science Foundation No. 2017A030312008.

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https://doi.org/10.1145/3185503

would be a great relief for the user. For the past decade, both industry and academia have devoted their efforts toward this goal.

Existing battery-free devices harvest energy from different sources, including solar energy, RF signals (e.g., References [4, 12]), ambient heat sources, or temperature changes (e.g., Reference [35]). They are limited to specific environments, which require sunlight, heat sources, or a powerful RF reader for battery-free RFID tags. Recent works (e.g., References [4, 24]) enable energy harvesting from ubiquitous ambient RF signals, where we can harvest tens to hundreds of microwatts. However, this amount is insufficient for wearable devices that need power for sensing, processing, and wireless communication.

Different from wireless sensor nodes, wearable devices are worn by users for long periods of time, thus they have the opportunity to harvest energy from the human body. As demonstrated in Reference [5], when performing various types of activities, e.g., opening a drawer, writing with a pencil, or taking a book off a shelf, an IoT device can harvest different amounts of kinetic energy. In addition to body motion, there are other energy sources such as body heat and respiration. These are all potential energy-harvesting sources for on-body devices.

As a first step toward this goal, in this article, we build a pair of battery-free smart shoes. We select this as the starting point for the following reasons. Besides the promising amount of kinetic energy available during walking or running, wearable devices coming in the form factor of shoes are gaining popularity. Shoes are worn by users for the majority of daily time, including the time spent in the office/school and wandering on the street. Shoes play an important role in many aspects, such as assuring pedestrian safety [10], navigation (e.g., Lechal [14]) and fitness tracking (e.g., Nike+ [22]). As listed in Section 2.1, we can envision a lot of interesting applications with a pair of smart shoes.

Although the idea sounds favourable, we encounter several challenges. Given a number of existing works on energy-harvesting shoes, we note that there is a gap between existing studies and our goal. Existing works on energy-harvesting shoes can generate about 1–2mW [7, 13, 27, 36]. This amount is insufficient for some power-hungry sensing hardware (e.g., inertial measurement unit) and wireless communication modules (e.g., Bluetooth). We further note that existing works can only utilize the energy harvested from one foot. During walking or running, our two feet can generate almost an equal amount of energy. Yet there is no existing feasible solution to combine these two parts of available energy to support a complete sensing system.

It is not trivial to enable the whole system running with the energy from two feet. There is no feasible solution to achieve this goal yet. We came up with the idea of enabling a data channel between two feet to coordinate these two distributed parts. Traditional communication methods (e.g., Bluetooth, WiFi) consume at least tens of milliwatts, which are too costly in our scenario. Instead, we choose ambient backscatter [17, 18]. It does not actively generate radio waves, but works by backscattering existing RF signals in the air, which consumes almost zero energy. Thus, the two feet communicate by ambient backscatter at nearly zero cost. The data channel combines these two distributed parts, and thus they can work together and each of them contributes its harvested energy to the whole system.

However, ambient backscatter suffers a high packet error rate during motion. Ambient backscatter transmits data at low rates (i.e., 100bps–10kbps). It can take up to 2 seconds to send a 256-byte packet [18]. Moving at a normal speed (e.g., 1Hz per foot) will cause changes within that time frame. Consequently, packet error rate increases significantly over static scenarios. Furthermore, the error rate is dependent on the moving speed, stride length, and ambient environment. Thus the error rate fluctuates significantly and the error control methods should dynamically adjust the tradeoff between redundancy and error-correcting capability. To address these challenges, we borrow the idea from rateless codes. When moving, the distance and orientation between two

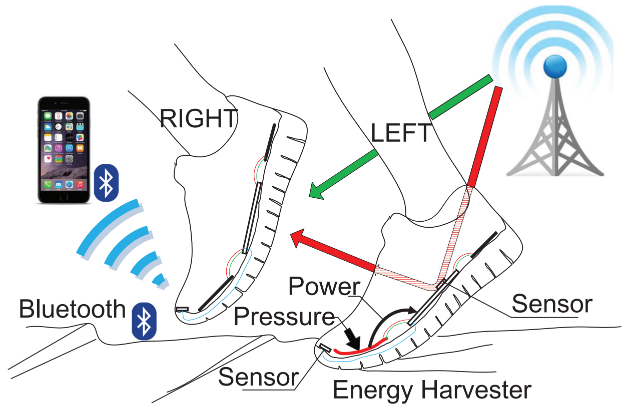


Fig. 1. System overview.

feet keep changing. The receiver has higher probability to successfully receive small chunks of data instead of complete packets. Instead of transmitting a complete packet, data are divided into several small chunks. Each time, the transmitter transmits a combination of these chunks. The transmitter keeps sending such chunks until the receiver acknowledges successful reception. The receiver can recover the original packet as long as it receives enough chunks for decoding. As we mentioned before, ambient backscatter is almost energy-free, thus continuous transmission would not consume much energy.

In our design, we allocate separate tasks to each foot. As shown in Figure 1, two feet have different hardware. One foot is equipped with sensing hardware (e.g., accelerometer, pulse sensor, temperature sensor). It senses user activity or ambient environment and informs the other foot of the results by ambient backscatter. The other foot can transmit this information wirelessly to the user's smartphone. In this way, we fully utilize the harvested energy on both feet.

Our platform is targeted for applications that are functioning only when the user is moving, such as location-tracking devices and pedometers. In implementation, we demonstrate our sensing platform as a pedometer. The evaluation results show that our system can wake up after 9 seconds' walking. It can transmit about 48 bytes of data every minute via Bluetooth when walking and 60 bytes every 48 seconds when jogging. The rateless mechanism can guarantee reliable data transmission in both indoor and outdoor scenarios. This system is also compatible with other sensors, such as pulse sensor and temperature sensor. For more discussion on supporting applications, please refer to Section 8.

We summarize our main contributions as follows:

(1) We design a battery-free sensing platform for wearable devices, in the form factor of shoes. It provides all the functionality of commercial wearable devices, including sensing, processing, and wireless communication.
(2) We are the first to enable the whole system running on the energy harvested from two feet, leveraging ambient RF signals. We design a rateless transmission mechanism according to the moving pattern of feet, which guarantees reliable data transmission and reduces transmission overhead.
(3) We demonstrate our system as a pedometer and conduct extensive experiments to evaluate our design in real-life scenarios. Evaluation results demonstrate the feasibility that wearable devices can be completely battery-free.

2 MOTIVATION AND DESIGN RATIONALE

Wearable devices are ubiquitous nowadays. They are playing important roles in a lot of applications. Wearable health kits provide health care for elderly people who are living alone, and give out alerts to doctors or family members when detecting abnormal physiology. Wearable devices may also provide cognitive assistance for those in cognitive decline. People who suffer cognitive decline have difficulties performing some basic functions. Wearable gadgets, such as Google Glass [6], can help them with cognitive tasks, such as face recognition and speech recognition.

Existing wearable devices rely on the battery for providing power for sensing, processing, and communication with smartphones or cloud servers. Both industry and researchers are trying their best to extend battery runtime. However, the majority of wearable devices require frequent charging. For example, the famous heart rate wristband, Mio [20], can only supply up to 20 hours' continuous heart rate monitoring. Frequent recharging is a challenging requirement in the above-mentioned scenarios. Elderly people easily forget to recharge their health kits. The situation is even more challenging for those in cognitive decline, who may be already suffering from memory loss. This requirement hinders the original intention for the wearable devices to be unobtrusive.

We are trying to overcome this shortcoming by energy harvesting. THe human body can generate a substantial amount of energy during daily life activities, which is a potential source for energy harvesting.

2.1 Why We Favor Shoes

Although there are many potential sources to harvest energy from human body (e.g., body heat, respiration, hand waving [5]), we prefer the form factor of shoes. Besides the promising amount of energy available during stepping, there are two main reasons.

First, shoes are necessary accessories during walking or running. Thus, we can envision a lot of interesting applications with energy-harvesting shoes. Here we name a few of them. When equipped with tracking devices, we can ubiquitously track the whereabouts of elderly people or children to prevent them from getting lost. With ultrasonic or infrared sensors, we can help blind people or patients with visual impairments to detect obstacles on the road. We can also enable fall detection for elderly people. Timely identification of a fall grants more rescue time.

The second advantage is attributed to the simple behaviour pattern of feet. The most prevailing form factor of wearable devices is the wristband. However, our hands will perform a lot of complicated activities, which makes it difficult for activity recognition and health monitoring. Thus, it may degrade the accuracy to some extent. Compared with hands, our feet are in much more simple states. Our feet may be either resting on the floor or lift in the air during walking and running. The simple behaviour pattern of the feet can improve the detection accuracy for a lot of applications (e.g., pedometers). Provided that there are existing commercial wearable products coming in the form factor of shoes (e.g., Nike+, Lechal), we believe that shoes are appropriate for mounting sensors.

2.2 Only One Foot is Insufficient

Existing works design different kinds of energy-harvesting shoes, either by shoe-mounted rotary magnetic generatos [13] or piezoelectric shoes [13, 36]. In this article, we limit our scope to piezoelectric shoes, for they can be easily incorporated into a sole structure. Confined by many design considerations (e.g., user comfort, weight, size), state-of-the-art piezoelectric shoes can generate about 1–2 mW energy [7, 13, 27, 36].

However, the energy is not accumulated linearly at each step. This is because the energy source is only intermittently available when the feet hit the ground. For the majority of time, the storage

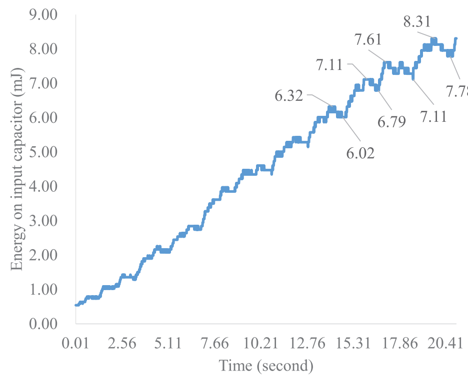


Fig. 2. Energy stored on a $47\mu F$ input capacitor.

capacitor is in a self-discharge (leakage) state. Leakage current increases exponentially with voltage [30]. This leakage effect is particularly severe when the voltage is high.

To illustrate this point, we redirect the current from the piezoelectric insole to a $47\mu F$ input capacitor. We put the insole into a shoe of a volunteer and ask him to walk at his preferred speed. Figure 2 shows the energy stored on the capacitor. We add the labels for the last four steps. From Figure 2, we can learn that, although we could get about 1mJ per step, we lost about 0.5mJ due to capacitor leakage. The leakage would become even more severe when the voltage increases. It indicates that storing an increasing amount of energy is exponentially hard.

Existing piezoelectric shoes focus on harvesting energy from one foot. On one hand, it wastes the energy available on the other foot; on the other hand, it is challenging to store a sufficient amount of energy on one foot. If we could combine these two parts of energy, we can double the total amount of available energy for our wearable devices. Furthermore, we could separate energy storage to two feet. It is a pity that there are no existing efforts devoted to bridge this gap.

2.3 Ambient Backscatter Can Bridge the Gap between Two Feet

To solve the aforementioned challenge, we come up with a solution to establish a data channel between two feet. The data channel could be used to coordinate these two distributed systems on two separate feet. Thus the two parts can make a whole system.

The data channel must come at a cheap price in terms of energy consumption. Traditional communication methods, such as WiFi, Bluetooh, or Zigbee, cannot work in such an ultra-low-power system, for they consume at least tens of milliwatts. Instead, we choose ambient backscatter communication [17, 18]. Different from the traditional radio communication, ambient backscatter does not generate radio signals, which is very power consuming. Instead, the transmitter modulates existing signals in the air for near-field communication, and the receiver uses only analog components for decoding. It only consumes several microwatts. Ambient backscatter working at 539MHz can communicate up to 75cm [17], which is enough for data transmission between two feet.

3 SYSTEM OVERVIEW

3.1 Design Goal

The goal of this study is to enable wearable devices to function normally without batteries. To be specific, it should provide:

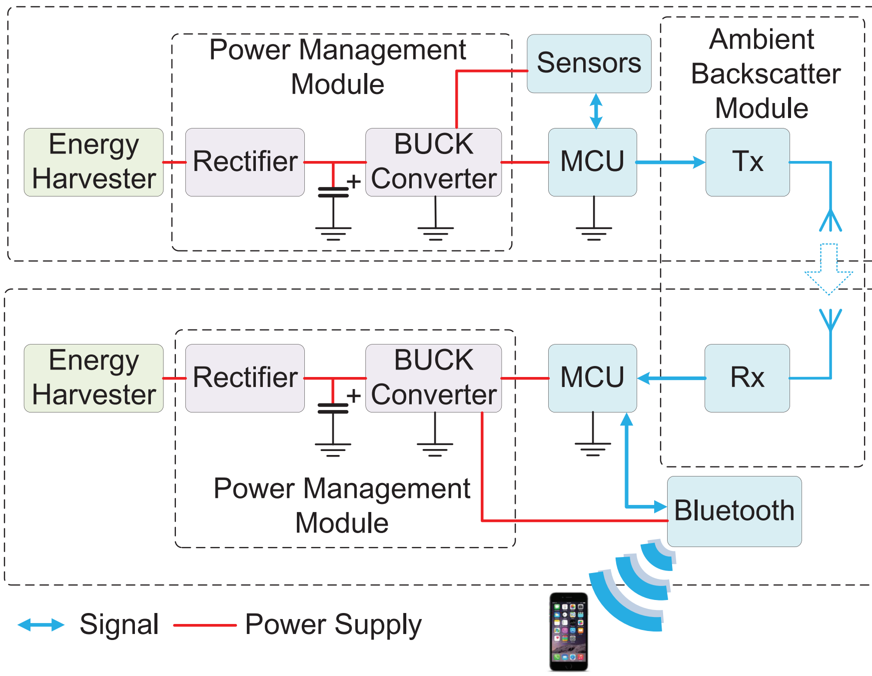


Fig. 3. System architecture.

- *Short Startup Time.* The system should start up shortly after the user starts walking.
- *Stability.* The system should be stable during walking periods. It should avoid frequent brownout when the user comes to a short pause, such as waiting for the elevator or lining up in a queue.
- *Proper functionality of sensors,* which depends on application scenario. It may be monitoring heart rate once per minute, or log the steps taken by the user, and so on.
- *Sufficient Bluetooth throughput,* which is also application-dependent. For the two above-mentioned applications, they may need to synchronize with users' smartphones once per minute, with heart rate or step counts as payload.

For the rest of the article, we demonstrate the system as a pedometer.

3.2 Design Overview

Figure 3 shows the overview of our design. We have two energy-harvesting insoles that can convert the foot pressure into electrical current, as shown in Figure 4. The electricity is rectified and stored at an input capacitor. When we walk for several steps and the voltage on the input capacitor accumulates to the threshold for waking up the power management module, the buck converter starts converting the voltage on the input capacitor into regulated voltage for supplying loads.

Each foot is responsible for separate tasks. In our design, we let one foot perform sensing and processing and let the other foot carry out wireless communication (i.e., Bluetooth) with nearby smartphones. We select Bluetooth for it is supported by the majority of commercial wearable devices. Both feet have ultra-low-power micro-controllers. The micro-controller, on the foot with sensors, buffers the sensor data, does data processing, and transmits the results (e.g., how many steps taken so far, instantaneous heart rate) to the other foot by ambient backscatter communication. The other foot receives the information and sends it out to the users' smartphones.

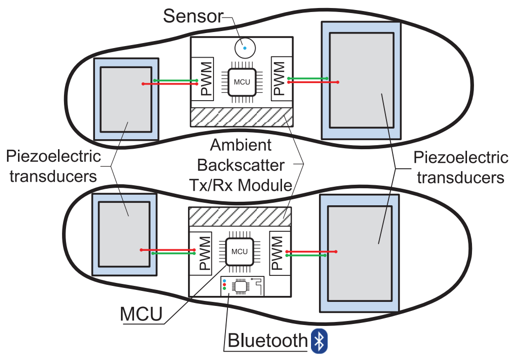


Fig. 4. Components on two shoes.

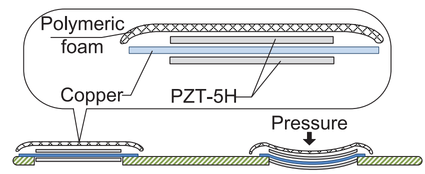


Fig. 5. Energy-harvesting Insole.

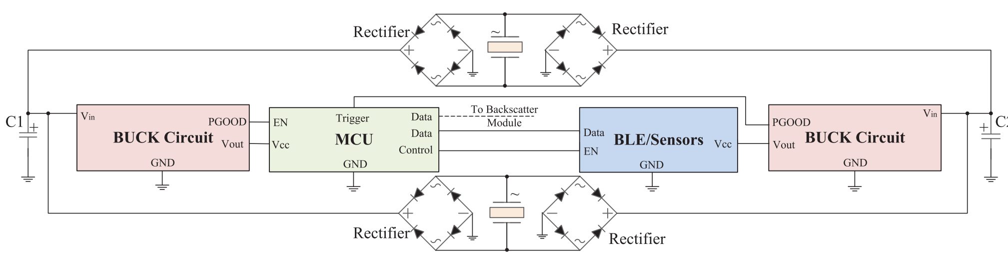


Fig. 6. Circuit diagram.

Thus, we enable the end-to-end functionality of wearable devices in a battery-free scenario.

4 INSOLE AND CIRCUIT DESIGN

In this section, we show the design details of the energy-harvesting insole and power-management circuits.

4.1 Energy-Harvesting Insole

We observe that during walking, there are two phases when the insole is under high pressure. An obvious one is the contact phase when the heel hits the ground. The other one is the propulsive phase, when the heel is off the ground and body weight is on the forefoot area. Thus, we mount piezoelectric materials in these two areas to convert pressure into electricity.

As shown in Figure 5, we drill two 5cm × 5cm holes on a 3mm-thick PVC plate, to mount PZT-5H bimorphs. When under pressure, PZTs flex and generate electric charge. We add a thin layer of polymetric foam over the PZTs to buffer the strike process, which also contributes to user comfort. The whole insole is 4mm thick and feels as comfortable as a normal insole.

4.2 Power Management Circuits

The power management circuits are used to transfer the unstable and alternating voltage generated from piezoelectric transducers into stable DC voltage. The circuit diagram is shown in Figure 6.

The two piezoelectric transducers in Figure 5 are connected in parallel, for we want more current instead of higher voltage. As they are not actuated simultaneously when stepping, we use separate full-wave bridge rectifiers to prevent them from canceling each other's generated voltage. The rectified charge is stored on input capacitors. The input capacitors are selected according to the load requirements. In general, it should satisfy

$$P_L \cdot t_L \leq \frac{1}{2} \cdot \eta \cdot C_{IN} \cdot \left(V_{IN}^2 - V_{TH}^2\right).$$

Here, the left-hand side is the amount of energy required by loads. V_{IN} is the voltage on the input capacitor and V_{TH} is the shunt off voltage threshold for the buck converter. η is the efficiency of the buck converter. The input capacitor should store enough energy for the loads before the buck converter shunts off. This could be achieved by adjusting the value of C_{IN} or letting V_{IN} charge to a high voltage.

As shown in Figure 6, we use separate input capacitors and buck converters for micro-controller and sensors/Bluetooth. The full-wave bridges provide isolation for each input capacitor, thus they can prevent some power-hungry sensors or Bluetooth from draining away the energy for micro-controllers. Another advantage of such design is that it enables the intended power-supplying sequence. For example, the micro-controller will wake up shortly after several steps, whereas it takes much longer to store enough power for Bluetooth. When the micro-controller wakes up, it consumes the energy from C_1, thus the voltage on C_1 will fall. For the two capacitors connected in parallel, the current from the piezoelectric transducers will be directed to this lower voltage capacitor until both V_{IN} are equal again. Thus, we can guarantee stable power supply for micro-controllers.

5 AMBIENT BACKSCATTER BETWEEN TWO FEET

We choose ambient backscatter to coordinate two feet, for it consumes almost zero power. Instead of generating radio signals, ambient backscatter works by modulating existing RF (e.g., TV, WiFi) signals in the air. To transmit a string of 0's and 1's, the transmitter switches between reflecting and non-reflecting states by switching the input impedance of the antenna in matched or mismatched states. In non-reflecting state, the receiver will only see the ambient signals; in reflecting state, the additional reflected wave from the transmitter will superimpose the original ambient signals and create changes in signal envelop. Thus, the receiver can distinguish these two states to decode the information. As there is no need for power-consuming RF oscillators and high-speed ADCs, it consumes almost zero power.

For ambient backscatter to work on a pair of shoes that users would wear and walk around, we identify two unique challenges.

5.1 Challenges

The first challenge results from motion. As mentioned before, the reflected wave would create changes in signal envelop. The reflected wave may either constructively or destructively superimpose on the ambient signals, which depends on the relative position of the transmitter and the receiver. During walking, the distance and orientation between the two feet keep changing. For one instant, the reflecting state at the transmitter side may correspond to a large signal amplitude at the receiver side; for the next instant, it may correspond to a small signal amplitude. When such transition happens during a packet transmission, errors are inevitable even with differential coding. To make the situation worse, ambient backscatter works at a low data rate (e.g., 1kbps). It requires more than 500ms to send a 64-byte packet. When walking at a normal speed, say, 1Hz per foot, channel conditions change dramatically within the span of a packet transmission. Thus, compared with static scenarios, the packet error rate between a pair of moving transmitter and receiver is significantly higher.

To get a basic idea, we do a measurement study with differently sized packets under four different scenarios, i.e., standing still, walking slowly (0.5Hz per foot), walking normally (1Hz per foot),

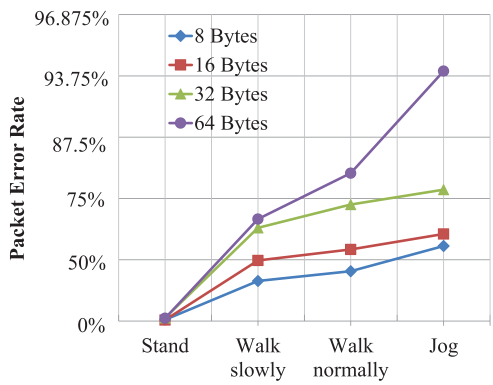


Fig. 7. Packet error rate for different sized packets under various speeds (y-axis in log scale).

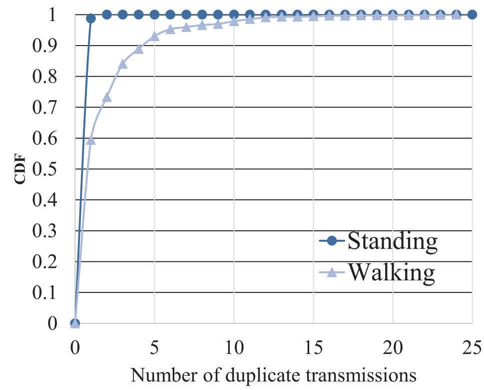


Fig. 8. CDF plot of duplicate transmission counts.

and jogging (1.5–2Hz per foot). The results are shown in Figure 7. From Figure 7, we can learn that with increasing packet sizes and moving speeds, the packet error rate grows.

The second challenge owns to the unpredictable packet error rate. The error rate is subject to many factors, such as the speed of walking, stride length, and ambient environment. When walking slowly with small stride length, the possibility of successful transmission is high; with increasing moving speed and stride length, the number of retransmissions required before successful transmission grows. Even the multipath effect from a passerby can create changes in signal amplitude, leading to decoding errors. Figure 8 shows the CDF plot of duplicate transmission counts for successfully transmitting a 16-byte packet under static scenario and moving scenario (i.e., walking at a speed of 1Hz per foot). In the walking scenario, for the majority of the time, it requires, at most, five times of duplicate transmission. However, in the worst case, it requires more than 20 times of retransmissions. Traditional error control methods work by adding a fixed ratio of redundancy in data transmission, which is unsuitable in this case where the error rate fluctuates significantly.

5.2 Transmission Mechanism Design

From the challenges illustrated above, we identify two characteristics. The first one is that short packets are favorable, as the transmission time is short and thus human motion is unlikely to change the channel condition within the time span of a packet transmission (e.g., 0.1s). The second challenge suggests that flexible adaptation to channel condition is highly beneficial [31].

To jointly tackle these two challenges, we borrow the idea from rateless codes. We divide the whole packet into k blocks of equal size. At each transmission, instead of transmitting a complete packet, we transmit a short sub-packet, which is a combination of some of the k blocks. The transmitter continuously transmits sub-packets until the receiver has received enough sub-packets for decoding.

There are many rateless codes, e.g., LT codes, random linear code. For a rateless code, if the receiver has to receive n sub-packets to fully recover the original packet, its decoding efficiency is defined as k/n. Although the decoding efficiency of random linear code is 1, it has high computation complexity, for it uses multiplication in encoding and decoding. In our design, we choose LT code, for it has low computation complexity. It uses only the lightweight XOR operation.

In LT code [19], there is a degree distribution function $p(d)(d = 1, 2, \ldots, k)$, which decides the degree of a sub-packet, i.e., how many blocks to be XORed together. At each transmission, the transmitter first draws a degree d from the degree distribution, and then randomly selects d out of the k blocks and these d blocks are XORed together to be an encoded sub-packet.

To optimize the decoding efficiency, we combine the moving pattern of the two feet to determine $p(d)$. In Reference [25], Rossi et al. proposed an iterative algorithm to find the optimal distribution. However, Reference [25] assumes error-free channels. To overcome this drawback, we combine the measurement results from Section 5.1 to refine the channel condition.

Initially, we set $p(d)$ to be the ideal soliton distribution. At each iteration, we find the packets that are received with low overhead, e.g., n is very close to k (decoding efficiency close to 1). Then we use the degree distribution of these low-overhead sub-packets to update $p(d)$. The algorithm will repeat this step until there is not much improvement in the overall decoding efficiency. Algorithm 1 shows the pseudo code and readers may refer to Reference [25] for the detailed algorithm. With this adjustment, the resulting $p(d)$ can capture the characteristics of the channel between two feet.

ALGORITHM 1: Algorithm

$p \leftarrow$ ideal soliton distribution, $cost \leftarrow \mathbf{0}_{1\times m}$, $N \leftarrow \mathbf{0}_{k\times m}$ ▷ m is the sample number
while $\|\Delta cost\| > \delta$ **do**
  for $i = 1$ to m **do**
    repeat
      Draw d from distribution p ▷ d is the degree of next packet
      Generate a packet P of degree d and transmit P
      $N_{d,i} \leftarrow N_{d,i} + 1$
    until Receive ACK from receiver
    $cost_i = \sum N_{*,i} - k$
  end for
  $\beta \leftarrow$ samples with cost below average
  $p_j \leftarrow \frac{\sum_{i\in\beta} \frac{N_{j,i}}{\sum N_{*,i}}}{|\beta|}$ for $j = 1, \ldots, k$
end while

As Reference [2] pointed out, the processing power of micro-controllers is advancing over the years and they are capable of processing rateless transmission.

6 IMPLEMENTATION

We implement the prototype in a pair of sport shoes. Two 3mm-thick PVC plates are cut into the size and shape of a shoe insole, such that they can be fit into the shoes. On each insole, there are two PZT bimorphs, as shown in Figure 5. The two PZT elements on each bimorph are connected together, forming one electrical polarity. The copper electrode between the two PZT elements forms another polarity.

The circuits are fabricated on a two-layer PCB. The buck converters are implemented using the LTC3588-1 from Linear Technology [16], with four selectable output voltages of 1.8V, 2.5V, 3.3V, and 3.6V. Each bridge rectifier comprises four 1N5819 Schottky diodes. We use ZXMN2F30FH n-channel MOSFETs as power switches to prevent the loads from draining the harvested energy before the storage capacitors have built up enough energy. The PGOOD pin from LTC3588-1 serves as the indicator for turning on/off the power switch.

We use the EFM32ZG110 [28] as the micro-controller, which is an ultra-low-power 32-bit ARM Cortext-M0+ processor running up to 24MHz. It has 4KB RAM and 32KB flash memory. It consumes only 0.9μA in deep sleep mode. To demonstrate the system as a pedometer, we

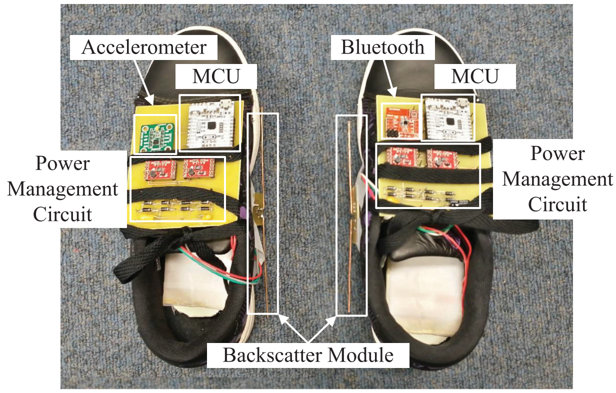


Fig. 9. Pictures of our prototype.

select the accelerometer ADXL362 from Texas Instruments as the sensor. The accelerometer is configured to 2g measurement range with a sampling frequency of 25Hz. The accelerometer has a deep 512-sample FIFO buffer, thus the micro-controller only needs to wake up periodically to get the three-axis acceleration data via SPI. As the accelerometer does not have an enable pin, we use a ZXMN2F30FH n-channel MOSFET as the control logic. The GATE of the MOSFET is connected to a GPIO pin of the MCU. On the other foot, the DA14580 [1] Bluetooth Smart Soc communicates with the micro-controller via USART. We develop an Andriod app to receive and display data transmitted from DA14580. The app runs on a Samsung Galaxy S4 smartphone with Android 4.4.2. The storage capacitor for the micro-controller, accelerometer, and Bluetooth are 47uF, 22uF, and 330uF, respectively. Their supplying voltages are set to be 2.5V, 1.8V, and 3.3V.

The ambient backscatter module is implemented as in Reference [17], using the parameters for 1kbps data rate. The antenna is tuned for 900MHz. We use a USRP N210 [3] to continuously generate 900MHz ambient signals. Although the prototype can be tested with TV signals, we use USRP, for it is easier to run controlled benchmark evaluation. Figure 9 shows our prototype.

7 EVALUATION

We evaluate the system from the aspects illustrated in Section 3.1.

7.1 System Start-Up and Brownout Time

In our scenario, our energy source is only intermittently available when the user is walking or running. It is preferred that our system can start up shortly after the user starts moving around. It is also preferred that the system can sustain for a period after the user rests, so as to prevent frequent brownout of micro-controllers.

As we mentioned before, the voltage on the input storage capacitor has to accumulate above a certain threshold to wake up the buck converter. Thus, there is a gap between the time when the user starts walking and the time when the system wakes up. We name this gap start-up time. Contrary to start-up time, the system can sustain for a short period after the user stops stepping, as long as the voltage on the input storage capacitor is above the shunt-off threshold of the buck converter. The system will brown out when the voltage drops below the threshold. We name this period brownout time.

We invite five volunteers to participate in the experiments. They are all college graduate students, one female and four male (BMI: 20, 20.8, 21.9, 22.9, 31). For each volunteer, we put the

Table 1. System Start-Up/Brownout Time

Experiment Number	Start-Up Time (sec)	Brownout Time (sec)
1	6.0	13.8
2	7.6	22.2
3	9.0	17.2
4	5.4	25.0
5	6.6	28.8

energy-harvesting insoles into his/her own shoes, and also attach the circuits to the shoes (as shown in Figure 9). They are instructed to walk at their preferred walking speed. Initially, there is no charge on the input capacitors. The results are shown in Table 1. The results for each volunteer are averaged over five runs of experiments.

From Table 1, we can learn that the system can start up shortly after the user starts walking. In our experiments, it takes 5–9 seconds' walking to wake up the system. We expect this period to be even shorter in practical use, for it is very likely that the input capacitors have some initial charge, which is the residual energy from the last walking period. The system can sustain for at least 13 seconds after the user rests, which can prevent the micro-controller from being powered off frequently when the user comes to a short pause, such as stops to open the door, or encounters a friend and pauses for a short conversation. Since micro-controllers consume tiny power in sleep mode (e.g., 0.9μA for EFM32ZG in deep sleep mode), it is reasonable that it can sustain for short periods when there is no energy source.

Besides accelerometers, when integrated with other sensors, we expect the micro-controller can also have short start-up time and sufficient brownout time, as micro-controllers follow the similar duty-cycle. For the majority of time, micro-controllers are in deep sleep mode, and only wake up periodically to get sensor readings and process sensor data.

7.2 Bluetooth Throughput and Transmission Frequency

Bluetooth throughput measures how many and how frequently data can be transmitted from our shoes to users' smartphones. In this subsection, we evaluate how many bytes can be transmitted by Bluetooth during walking (1Hz per foot) and jogging (1–2Hz per foot) periods. There is no charge on both capacitors at the beginning of each experiment.

Bluetooth consumes much more power than the micro-controller and accelerometer. To save energy, it is powered off for the majority of time, and only wakes up periodically to transmit data. When the input capacitor for Bluetooth (i.e., C_2) has accumulated enough energy, it will signal an interrupt to the micro-controller. The micro-controller will turn on the power switch to power on Bluetooth and wait for connection with the smartphone. When connected, Bluetooth will continuously transmit data to the smartphone until the voltage on C_2 drops below the shunt-off threshold of the buck converter. The results are shown in Table 2.

On average, during walking, Bluetooth can transmit about 48 bytes of data per minute. The first transmission starts after 1.5 minutes' walking. During jogging, it can transmit about 60 bytes every 48 seconds. The first transmission starts after 1 minute on average.

The system is suitable for applications that do not require always-on Bluetooth connection and only need to update information periodically. For applications such as pedometers and heart rate monitors, it is sufficient to synchronize with the smartphone once per minute; 48–60 bytes per minute throughput is adequate for carrying information about timestamps and step counts/heart rate.

Table 2. Bluetooth Throughput

	No.	Duration	Throughput	First Transmission Time
	1	10min	489 bytes	56sec
	2	10min	426 bytes	1min 40sec
Walking	3	10min	535 bytes	1min 14sec
	4	11min	492 bytes	2min 0sec
	5	11min	541 bytes	1min 21sec
	1	8min	610 bytes	38sec
	2	10min	535 bytes	1min 1sec
Jogging	3	10min	856 bytes	1min 44sec
	4	10min	718 bytes	1min 23sec
	5	10min	901 bytes	53sec

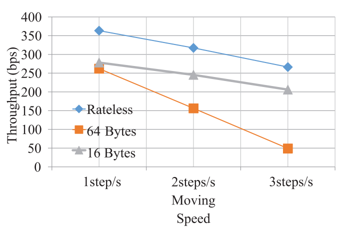


Fig. 10. Different moving speeds.

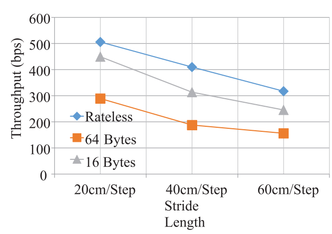


Fig. 11. Different stride lengths.

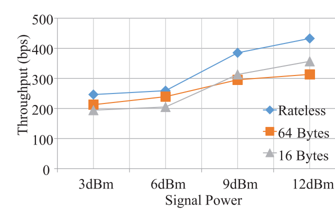


Fig. 12. Different signal power.

7.3 Performance on Rateless Transmission

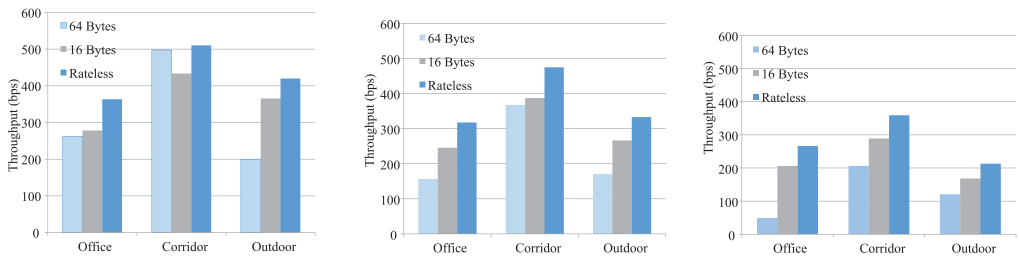
In this subsection, we show the evaluation results on rateless transmission. From Figure 7, we can learn that the packet error rates are very high for the 32-byte case and 64-byte case when moving fast. Although the 8-byte case performs better than the 16-byte case, there is a tradeoff between packet size and the overheads of preambles and headers. In our implementation, we use sub-packets with 16-byte data.

We compare our design with two other mechanisms: directly transmit a complete packet with 64-byte data and divide the original packet into four sub-packets, each with 16-byte data, and transmit the short packets sequentially.

We vary four testing parameters, including moving speed, stride length, signal power, and testing environment. For each combination of parameters, we test each mechanism for 10 minutes.

7.3.1 Moving Speed. Figure 10 shows the results under different moving speeds. The default stride length is 60cm. With increasing speeds, transmitting long packets is not as robust as transmitting short packets, for the channel condition changes dramatically during the transmission time span. On average, the rateless mechanism outperforms the other two mechanisms by 69% (64 bytes) and 30% (16 bytes), respectively.

7.3.2 Stride Length. Figure 11 shows the results under different stride lengths. The default moving speed is 1Hz per foot. With small stride length, short packets can be correctly received, but long packets suffer high packet error rate, since they require longer transmission time. All the performance drop with increasing stride length, for the distance between the transmitter and the receiver increases. On average, the rateless mechanism outperforms the other two mechanisms by 98% (64 bytes) and 24% (16 bytes), respectively.



(a) Moving at 1 step per second. (b) Moving at 2 steps per second. (c) Moving at 3 steps per second.

Fig. 13. Data transmission ratios in three different environments.

7.3.3 Signal Power. Figure 12 shows the results for different signal power. The bandwidth of USRP is set to 6MHz, which is the bandwidth of TV channel. we measure the signal power at the transmitter's side, using Rohde & Schwarz spectrum analyzer with a VERT900 antenna. The default moving speed and stride length are 1 Hz per foot and 60cm, respectively. In this figure, it is counterintuitive that directly transmitting 64-byte packets performs better than transmitting 16-byte short packets when the signal power is 3dBm and 6dBm. Although short packets have lower error rates, but they also have higher overheads. On average, the rateless mechanism outperforms the other two mechanisms by 35% (64-bytes) and 21% (16-bytes), respectively.

7.3.4 Testing Environment. We test the three mechanisms in three different environments, an office cubicle, an empty corridor outside the office and an outdoor open ground in the campus. We test with three different moving speeds and the results are shown in Figure 13.

In general, the performance is best in the corridor, for the experiments are conducted in a public holiday and there are few people passing by the corridor. Different from the corridor, inside the office, there are a lot of objects and equipments that may reflect the ambient signals, making the multipath profile much more complicated than the empty corridor. In the open ground, the performance is susceptible to the nearby environment. When there are passengers walking by, it would cause interference to the transmission.

With increasing speeds, the overall performance of the three mechanisms drop. From Figure 13, it is clear that rateless mechanism is more robust under different environments.

8 DISCUSSION

In this section, we discuss some practical issues.

Start-Up Delays. We demonstrate our platform with an accelerometer. There is a start-up delay, where the users have to walk several steps before the accelerometer can start sensing. For some applications that need to accurately count the number of steps taken, such as the pedometer, the results can be calibrated to improve accuracy. For example, for each walking or running period, the actual step counts are the number we get from the accelerometer plus some small constants (e.g., 3, 4, 5), which may be user dependent.

Compatible Applications. We demonstrate our sensing platform as a pedometer. According to the requirement illustrated in Section 3.1, our sensing platform can support many other sensors. Take a pulse sensor for an example. First, the toe is an appropriate place to measure heart rate with a PPG sensor. Second, although the energy-harvesting module may not support instantaneous heart rate monitoring, it can measure heart rate periodically, say once per minute, which is sufficient for daily health tracking. Last, as in many commercial heart rate monitors [20], we only need to send the heart rate information to smartphone, not the snippets of heart signal, the 48–60-byte Bluetooth throughput is sufficient to include both timestamps and heart rate information. In addition to sensors for personal tracking or monitoring, it can also mount sensors for sensing ambient temperature, humidity, and air condition, which are often used in crowd-sensing applications. The rewards from crowd-sensing applications may encourage users to walk more and exercise more.

Rateless Transmission. We use rateless transmission to tackle the fluctuating error rate during ambient backscatter. Although backscatter communications work the best when two feet are close to each other and the walking/running cycles are easy to detect using IMU (inertial measurement unit) sensors, the sensing and processing may consume extra energy for applications other than pedometer. Furthermore, ambient backscatter consumes nearly zero energy, hence continuous transmission is still more energy efficient compared with BLE/Zigbee. Although the throughput of ambient backscatter is low, it is sufficient to transmit control message and data between two feet. Thus, it is suitable to serve as a data channel in such a low power platform.

Limitations. One limitation of this design is that it cannot support some critical applications, such as location tracking for children or elderly people who are suffering from Alzheimer's disease. Although we can combine energy from two feet, the total amount is still insufficient for supporting GPS and cellular communication. For these applications, our design can help to extend the battery life to some extent, so that the frequency of battery replacement or recharging may be reduced. Another limitation of this design is that the design is hard to generalize to other wearable devices such as smart glasses, wristbands, and chest bands. For these gadgets, which cannot obtain as much kinetic energy as shoes, they may harvest energy from other sources, such as body heat, heartbeat, and respiration. Although these sources are insignificant compared to kinetic energy, they are always available. The devices may store the energy when the user is sleeping or at rest and use the stored energy when functioning.

9 RELATED WORKS

9.1 Energy-Harvesting Shoes

By means of energy generation, existing works on energy-harvesting shoes can be generally classified into two categories: shoe-mounted electromagnetic generator and piezoelectric shoes.

The electromagnetic generator is a well-proven technology to transform mechanical energy to electrical energy, which is widely used in electric power grids. The principle behind electromagnetic generators is Faraday's law of induction. Faraday's law points out that an electrical conductor that encircles a varying magnetic flux can generate electrical voltage. By designing the rotary methods, the force exerted during heel strike can be used to rotate the magnet or surrounding coil, and thus produces power. This method is favored for its high conversion efficiency. Kymissis et al. [13] achieved an average power of 0.23 watts using this method, with the walking speed of 1Hz per foot. However, the solid mechanical generator is usually heavy and cumbersome, which makes it hard to be integrated into shoes unobtrusively.

An alternative approach is to use piezoelectric materials. Piezoelectric materials can generate electric charge in response to applied mechanical stress. There are two methods to use piezoelectric materials to harness kinetic energy during walking. The first one is to use PVDF (polyvinylidineflouride) to convert the stress and stretch into electricity when bending the ball of foot. The second is to use piezoceramic to exploit the high pressure exerted in a heel strike. The prototype designed in Reference [13] shows that we can get 1.1mW from PVDF stave and 1.8mW from PZT Unimorph. In a recent study [36], the authors considered both the performance and durability of the PVDF, and designed a sandwiched structure. Their harvester provides about 1mJ per step. Compared with electromagnetic generators, the energy conversion efficiency is two orders of magnitude lower. However, piezoelectric materials are lightweight and can be easily incorporated into an insole structure.

In our study, we prefer piezoelectric shoes to electromagnetic generators, for we want to be unobtrusive and do not want to add too much weight to our footwear. In our experiments, for different subjects, our energy-harvesting insole can generate about 1–2mW per step, which is comparable to existing works.

9.2 Ambient Backscatter Communication

Liu et al. [17] first proposed ambient backscatter communication, which does not need a powerful reader to generate continuous carrier waves. Instead, it directly modulates the ubiquitous TV signals in the air. They demonstrated that their prototype can communicate up to 2.5 feet without any dedicated reader, only by energy harvesting from ambient RF signals. Parks et al. [23] designed multi-antenna cancellation techniques and a low power coding scheme for ambient backscatter, using only analog components without any digital computation. They significantly improved the communication rate and distance of ambient backscatter. Liu et al. [18] enable full-duplex ambient backscatter, which gives a way for the receiver to provide instantaneous feedback to the transmitter. Both the transmitter and receiver consume less than 1μW.

Besides TV bands, there is also research on ambient backscatter utilizing other RF spectrums, including Wi-Fi [11], Bluetooth [9], and FM bands [29]. In Reference [34], the authors proposed frequency-shifted backscatter, where the tag shifts the carrier signal to a non-overlapping frequency band and thus separates the spectrum of carrier wave and backscattered signals.

Based on existing works on ambient backscatter, we design a rateless transmission mechanism that is suitable for data transmission between two feet in motion. Experiment results show that our mechanism is robust under different scenarios.

9.3 Ultra-Low-Power Sensing Platform

There are a lot of research efforts devoted to designing ultra-low-power sensing platforms. WISP [26] is an RFID-based sensing platform. Based on WISP, researchers made improvement to provide more code space and RAM, and reduce energy consumption [32]. Zhang et al. [33] identified that given the low-power backscatter communication and ultra-low-power sensor modalities, energy consumption for computation is the bottleneck. EkhoNet focuses on reducing the power consumption in the computation pipeline and transfers raw sensor data by backscattering. Thus, they reduce the end-to-end energy consumption to tens of μW. Lee et al. [15] proposed a mm^3 scale general-purpose sensor node platform. It has an optical receiver for optical communication.

Different from existing works, we propose a battery-free sensing platform for wearable devices. In our scenario, we cannot rely on any dedicated powerful reader. Although there is the possibility for our smartphones to serve as the reader, it would largely shorten phones' battery runtimes. Furthermore, different from wireless sensing nodes, wearable devices should communicate directly with commercial smartphones for data analysis and synthesis. The most popular communication protocols are WiFi, Bluetooth, or ANT+, all of which consume much more energy than backscatter communication. Thus, existing ultra-low-power sensing platforms are not suitable for wearable computing.

This article is based on our previous article [8]. We redesign the rateless transmission mechanism to reduce computation overhead by replacing the multiplication operation with the lightweight XOR operation.

10 CONCLUSION

In this study, we have designed a battery-free platform for wearable devices in the form factor of shoes. The platform runs solely on the harvested energy from human walking or running. It supports sensing, processing, and wireless communication with smartphones, covering all the functionality of commercial wearable devices. We have achieved this goal by combining the harvestable energy from two feet. Each foot performs separate tasks and two feet are coordinated by ambient backscatter. Considering the motion pattern of human feet, we have designed a rateless transmission mechanism to improve the overall throughput and reduce overhead in data transmissions. We have implemented a prototype to demonstrate the feasibility of our idea. Evaluation results show that our design is robust enough for practical use. We believe that our framework will foster a lot of interesting applications that were previously impossible.

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Received July 2016; revised May 2017; accepted January 2018