A Study on Energy Harvesting Aware Routing for Vibration-Motivated Wireless Sensor Networks *

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Abstract

Extracting an electrical energy from various environmental sources, called energy harvesting (or energy scavenging), has been an issue and attracting researchers' attention in energy replenishable networks. In particular, a piezoelectric device based energy harvesting from ambient vibrations is a promising technique for easy of battery energy replenishment in vibration-motivated wireless sensor networks (WSNs). In this paper, we first address two major issues of vibration-based energy harvesting: impact spread and energy conversion. The overall analyses and preliminary results become a foundation in developing an energy harvesting aware routing protocol. Then we discuss the design constraints and challenges in developing the proposed routing protocol, and show a research potential in the area of vibration-motivated WSNs.

Keywords: Energy harvesting, Piezoelectric transducer, Routing, Vibration, Wireless sensor networks.

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1 Introduction

A wireless sensor network (WSN) consists of a large number of small devices (later nodes) equipped with sensing, computing, and communicating facilities [3]. Recent technological advances have fueled the development of a tiny, low-cost, and low-power node feasible and applicable to a wide range of applications built for WSNs. For example, WSNs have been integrated with structural health monitoring systems [17, 7] that are designed to detect and locate the structural damages in such as bridges, buildings, dams, ships, aircrafts, etc. Each node equipped with a vibration detecting card can be installed in a bridge and continuously monitors a structural state by measuring the ambient vibrations caused by passing vehicles [17] or trains [7]. We envision that WSN and its technology will be penetrated into our daily life and become a ubiquitous communication infrastructure in the near future.

However, due to a limited amount of battery energy, there has been a great deal of research efforts on the developing energy aware techniques in the WSNs. Particularly in routing, each node plays a role as either a sensed data sender or a router. Thus, it is essential to judiciously reduce the energy spent for communication activities including transmission, reception, and forwarding without degrading the communication performance such as a network lifetime. Also since nodes are usually required to operate for a long period in an unattended environment, it is inconvenient or hard (if it is not impossible) to either replace or replenish the battery.

In light on this, researchers in the academy and industry have been focusing their attention on the extracting of electrical energy from various environmental sources, called *energy harvesting* (or *energy scavenging*), for easy of battery energy replenishment. The environmental sources include vibrations, magnetic fields, thermal gradients, lights, kinetic motions, shock waves, etc. They motivate to generate an electrical energy through the combination with available components including piezoelectric, magnetoelectric, thermoelectric, and semiconductor, in which all these components have inherent pros and cons. When vibrations are a dominant source of energy and solar light is not always available, however, it has been found that piezoelectric-based energy harvesting is the most promising technique [16]. Here, vibrations can be generated in various places such as rotating machineries or engines, bridges due to passing vehicles or trains, buildings or dams due to wind or flowing water, etc.

In this paper, we address several key issues in designing an energy harvesting aware routing protocol with a piezoelectric device based energy harvesting technique in vibration-motivated WSNs. The current progress of our work is summarized in three folds:

- First, we are developing a simple model of impact spread to facilitate the estimation of impact force over time and distance, in which diffusion equation is used for easy of analysis. The impact spread is also simulated and observed with a series of multiple impact sources.

- Second, we are proposing an explicit interpolation function based on a modified inverse Béizer curve technique to support a seamless energy conversion because of a limited number of original data points obtained from a piezoelectric device. The proposed interpolation function is easily implementable under low computational complexity and overhead, and the preliminary results are presented.

- Third, we are developing an energy harvesting aware routing protocol primarily based on the broadcast-based forwarding techniques. Observations and design constraints and challenges are discussed to characterize the proposed routing protocol.

The rest of paper is organized as follows. The prior work is carefully reviewed and analyzed in Section 2. A simple model of impact spread and an energy interpolation function are presented in Section 3. Section 4 is devoted to discuss the design constraints and challenges in developing an energy harvesting aware routing protocol. Finally, we conclude the paper with future directions in Section 5.

2 Background and Related Work

Since wireless communication could be responsible for more than half of total energy consumption [19], a lot of research effort has been devoted on the developing power efficient or power aware routing techniques [29, 6, 21, 22] in wireless multi-hop networks. In WSNs, in spite of energy aware routing techniques, the maintenance cost including the locating and replacing the batteries becomes non-negligible, because nodes are supposed to operate for a long period in an unattended environment.

Therefore, a number of recent studies have been conducted with a set of re-chargeable (or renewable) nodes in WSNs [33, 14, 15, 23, 13, 37], where each node's battery is replenished by energy harvesting from various environmental sources [31, 14, 33, 27, 25, 16]. In [14, 13], a solar-based energy harvesting model is presented and the model is applied to scheduling and routing methodologies. It is shown that the proposed energy harvesting aware routing increases network lifetime compared to that of traditional battery aware routing schemes. Kar *et al.* [15] proposed several threshold policies to maximize the communication performance by activating the node dynamically, in which each node is assumed to be randomly recharged and it changes its state into one of three states, active, passive, or ready. Voigt *et al.* [33] proposed a solar aware routing, in which a packet is forwarded to the node powered by the solar energy.

For easy of battery replacement and energy replenishment, harvesting energy from ambient vibrations using a piezoelectric transducer has been investigated and applied to the wide range of applications [12, 30, 32]. Hausler *et al* [12] proposed the implantation of piezoelectric polymer patches into a living body to harvest energy from breathing. Body heat, blood pressure, and breath pressure have the potential of generating electric energy. In [30], piezoelectric materials are used in the soles of shoes, where an electrical power is generated through walking. Also mechanical flow energy in oceans and rivers is also utilized to convert electrical energy by using piezoelectric polymer actuators [32]. They provide a large amount of electrical power levels due to the vast size of the flowing water resources.

In WSNs, since nodes have no or extremely low (if any) mobility under low battery power and limited computing and communication capabilities, a broadcast communication paradigm is preferred [3] because of its simplicity and low routing overhead. There has been an active research on a probabilistic broadcast, called gossiping [11], that decides whether a node forwards a packet with a certain probability (a gossiping probability) to reduce a number of routing packets in a network. It has been widely applied to WSNs [4, 24, 20, 18] because traditional flooding schemes may incur the broadcast storm problem [26] and consume a serious amount of energy. Kini *et al.* [18] compared the communication performances of several gossip variants in terms of message coverage, energy efficiency, per hop latency, and message overhead. In fact, since each battery-dependent node has a fixed amount of energy, it will use up the energy and die ultimately regardless of the energy-efficient techniques.

In addition, by using the broadcast nature of wireless medium, an opportunistic routing is recently emerging [5, 35, 8, 40, 36, 28]. The idea of this routing is that a sender does not pre-select a particular route or forwarder but broadcasts its data packet and thus, one of available receivers for forwarding is selected. It is different from the traditional routing techniques, where the best path between source and destination is chosen and packets are forwarded to the corresponding next hop so that multiple packet retransmissions may be occurred in the presence of fluctuating quality of wireless link.

In summary, little effort has been devoted in exploring an energy harvesting aware routing in the realm of vibration-motivated WSNs.

3 Vibration-Motivated Energy Harvesting

In this section, we first present a simple model of impact spread based on diffusion equation. Then we propose an interpolation function to support a seamless energy conversion.

3.1 A Simple Model of Impact Spread

To build a simple model for measuring the impact spread from the node located in l at t, we consider an exponential normal distribution function. The impact spread function measures an amount of impact from the node located in l at t, and it is expressed as,

$$S(l-\xi, t-\tau) = \frac{1}{(4\pi\kappa(t-\tau))^{n/2}} e^{-|l-\xi|^2/4\kappa(t-\tau)}, \tag{1}$$

where ξ and τ are the impact location and its generation time, respectively, Also $|l-\xi|$ is a distance, and n is a dimension. In addition, κ is a proportionality factor which measures the rate of transferred energy from one location to another. Eq. 1 is known as the fundamental solution of the diffusion equation expressed as,

$$u_t + k\Delta u = \delta(l-\xi)\delta(t-\tau), \tag{2}$$

where δ is the Dirac delta function [34]. Eq. 2 is interpreted by the partial differential equation, which describes the behavior of flow with the concentrated unit source located in $l = \xi$ at time $t = \tau$. More precisely, it explains the movement of spread when the source turns on only the specific position ξ and instant τ without involving any other energy sources for entire (l, t) except (ξ, τ). Due to this *discrete* nature of the fundamental solution, Eq. 1 can be used to model the impact spread for a single source of impact.

Then we extend Eq. 1 to consider a series of impacts which are generated at different time, but each individual impact is affected by prir impacts. Suppose we have m impacts generated in different locations $(\xi_1, \cdots, \xi_m)$ at different times $(\tau_1, \cdots, \tau_m)$. Also we assume different proportionality constants $(\kappa_1, \cdots, \kappa_m)$ and impacts of each event $(\Gamma_1, \cdots, \Gamma_m)$, and only consider 2-dimensional spatial domain (n = 2). Then we can define the impact spread function for i^{th} impact by,

$$S_{\Gamma_i}(l-\xi_i, t-\tau_i) = \frac{\Gamma_i}{4\pi\kappa_i(t-\tau_i)} e^{-|l-\xi_i|^2/4k(t-\tau_i)} \tag{3}$$

For the purpose of combination of impact events, we also assume $0 = \tau_1 \leq \tau_2 \leq \cdots \leq \tau_m$ without loss of generality. Thus, the total amount of impacts for i^{th} event is formulated as,

$$S(l, t) = \sum_{j=1}^{i} S_{\Gamma_j} \tag{4}$$

Table 1: Properties of PFCB-W14

Property	Value
Dimensions (mm)	132 $\times$ 14 $\times$ 1.3
Resonance frequency (Hz)	30$\pm$1
Bending stiffness (N/m)	56
Maximum bending displacement (mm)	50
Maximum voltage (V)	200

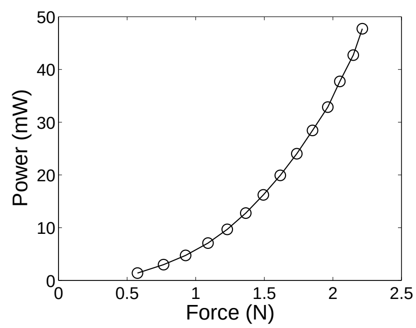

Figure 1: The power generation against the impact force using PFCB-W14.

Since diffusion equation is one of the basic equations, we expect that our approach can be extended to meet more realistic physical phenomena, where more general energy spread functions are required. The extension can be formulated by adding more sophisticated differential equations and terms. Due to computational complexity and overhead, however, we do not consider the extended equation in this paper.

3.2 Mapping Mechanical-to-Electrical Energy

In this paper, we use a piezoelectric fiber composite bimorph (PFCB) W14 as a piezoelectric component to trap an environmental energy and transform into the mechanical vibration energy, and its properties are summarized in Tab. 1. The PFCB W14 based piezoelectric transducer consists of a piezoelectric generator and a storage circuit. The conversion from mechanical to electrical energy is obtained by the direct piezoelectric effect in the generator. The amount of energy generated is directly related to the extent to which a ceramic element is deformed in the generator to the impact force that incurs a *vibration*. Once the energy is generated, it is saved into a storage circuit such as a capacitor or a re-chargeable battery, where there is the maximum capacity. Thus, the energy generated cannot be stored beyond this capacity limit. By using the PFCB-W14, we have obtained a finite set of experimental data points in Fig. 1.

Due to a limited number of data points obtained, it is essential to approximate a new data point between known data points to construct a conversion function of mechanical-to-electrical energy. Thus interpolation techniques from numerical analysis are used to generate a function that can estimate the intermediate data points. Depending on the constraints such as an accuracy, complexity, and smoothness of interpolation, various alternatives can be used to create an interpolation function [9].

To develop an interpolation function based on the given data set, we primarily focus on whether the function can generate a curve that is smooth and close enough to reflect the original data set. Also the function should be simple so that it can easily control the shape of curve having a large number of data points. However, interpolation technique basically generates a polynomial function that must pass the known data points. By using a higher dimensional polynomial, we can make the curve smooth enough but the overall shape is deteriorated to match a *possible* original shape from the given data set. In case of considering overall shape by using lower order polynomials, additional conditions are required to make a smooth connection between sub-curves defined in sub-interval as Spline approximations [9] but they incur complicated formulas. Thus, although it is a conflict requirement, we should carefully select an interpolation technique not only generating the curve with smooth connection but also having a simple formula with less computational complexity and overhead.

In this paper, we deploy a method based on Bézier curve [9] to fulfill the aforementioned requirements because it generates a smooth curve and has a simple formula. It is defined within interval $[0, 1]$ and formulated with the basic Bernstein polynomials,

$$B_{(i,n)}(t) = \left(\begin{array}{c} n \\ i \end{array} \right) t^i (1-t)^{n-i}, \quad \left(\begin{array}{c} n \\ i \end{array} \right) = \frac{n!}{i!(n-i)!}, \tag{5}$$

where $0 \leq i \leq n$ and $t \in [0, 1]$. However, there are two issues in the Bézier curve: (i) The curve is defined as an implicit curve $(x(t), y(t))$ based on t instead of an explicit function such as $y = f(x)$. Therefore we cannot directly estimate the energy value (function of $y(t)$) for any intermediate force value (function of $x(t)$). Although we can expect to have strictly increasing $x(t)$ values, the difference between x_i variables obtained from experiment is not uniform and thus, $x(t)$ is not the first order polynomial; and (ii) The curve is only guaranteed to pass the initial point at $t = 0$ and terminal point at $t = 1$ and thus, the other points might not be included in the curve even though they might be located nearby.

To resolve these, we investigate an inverse Bézier method to produce an explicit function based on the Bézier method. However, we observe that this approach affects to overall shape of the interpolation and deteriorates the quality. In order to eliminate the fluctuating portion but keep the structure of original Bézier method, we modify

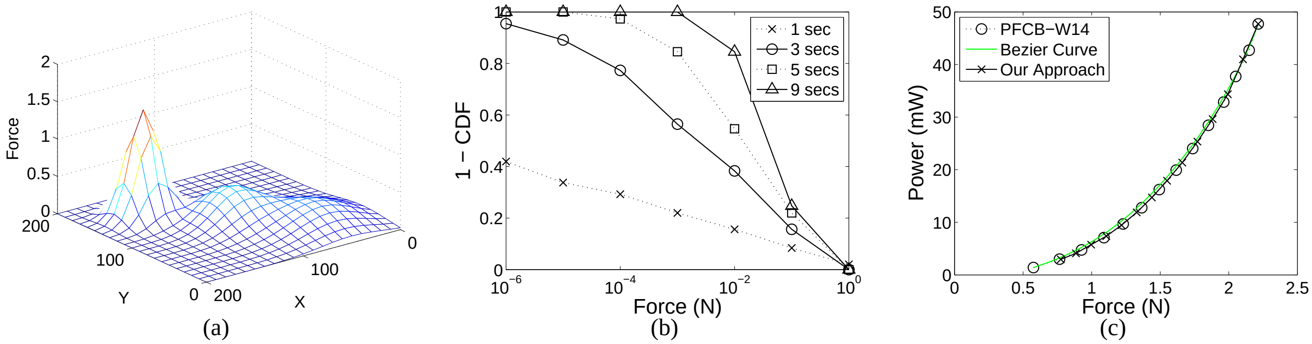

Figure 2: The preliminary results: (a) The spread of a series of impacts over time; (b) The cumulative forces after a single impact over time; and (c) Comparison between the Bézier curve and our approach (modified inverse Bézier curve) in the presence of a limited number of original data set obtained by PFCB-W14.

the inverse Bézier method. In this paper, we use a heuristic approach by adding a set of virtual data points in small t and managing the curve to generate plausible $y(t)$ values. The rationale behind this is to generate a simple interpolation function, in which the curve must pass the given data points.

3.3 The Preliminary Results

To examine the proposed idea, we use the Matlab for mathematical analysis and develop a customized discrete-event driven simulator using CSIM [1] for conducting our experiments. We use a 200 $\times$ 200 (m^2) rectangular network area, where 441 nodes are located in a grid topology (21 $\times$ 21 nodes). The impact arrival rate follows the Poisson distribution with a rate of λ, and the impact force is uniformly selected between 0.5 and 2.5 (N) values based on the PFCB-W14. To gain a realistic impact force, we also scale distance down to 0.001 times and set κ as 0.1. In Fig. 2 (a), we visualize the spread of a series of impacts occurred consecutively with 2 seconds gap with randomly chosen impact forces. Fig. 2 (b) shows the number of nodes that has the corresponding forces and its cumulative statistics. After the impact, the force decreases rapidly as the time increases. In Fig. 2 (c), we compare our approach with both curves derived from the original data set with PFCB-W14 and Bézier technique. In contrast to the Bézier curve, which does not necessarily pass to the original data points except begin and end points, our curve based on the modified inverse Bézier technique passes the original data points for entire impact forces. Thus, the proposed interpolation function is proven to be a viable approach for finding the reasonable intermediate data set based on the limited number of original data set.

4 Energy Harvesting Aware Routing Approach

In this section, we first characterize the energy harvesting aware routing through the observations. Then we discuss the design constraints and challenges in developing the routing protocol.

4.1 Observations

In vibration-motivated WSNs, sensing and forwarding operations are initiated by an event of vibration which is originally converted from the impact force. Upon re-charging the energy through the harvesting procedure, node is able to re-initiate a network device and ready for communication. Due to the variable amount of energy, it is a critical issue to judiciously choose an energy rich forwarding node. The following observations characterize the proposed energy harvesting aware routing and support our research motivation:

- Although nodes have little (or no) mobility, due to the limited amount of energy, it is an overhead to find an energy optimal path to the sink for every routing by exchanging route discovery packets.

- The event of vibration has mobility, i.e. vibrations can occur anywhere within the network, and its energy harvesting period varies depending on the amount of impact force. Thus, a fixed-route based routing does not work well because of fluctuating availability of energy for communication.

Improving energy conservation and reducing routing overhead are conflicting requirements, and optimization of both is admittedly complex.

4.2 Design Constraints, Challenges, and Discussion

Based on the observations, we have identified the following design constraints for developing an energy harvesting aware routing protocol: (i) Simple and localized the routing decision; (ii) Minimized the route discovery or maintenance overhead; (iii) Robustness under unavailability of energy or node failure; and (iv) Awareness of harvesting energy. To address these constraints, we propose an energy harvesting aware routing protocol primarily based on the broadcast-based forwarding techniques.

In the proposed routing protocol, each node broadcasts a packet with a forwarding probability that is formulated by multiple factors, such as a remaining energy, an expected harvesting energy, a distance/direction to the sink, a number of neighbors, etc. The rationale behind this approach is that it localizes the routing decision into the single-hop away packet receivers. Also in contrast to the traditional best-path routing that easily dominates the energy, it is a per-hop basis routing and minimizes the overhead of a route discover or maintenance procedure. In addition, due to unavailability of energy or node/link failure in vibration-motivated WSNs, a single-path based routing is not reliable, i.e. a loss probability of link in WSNs is well above 50% [39].

To develop the proposed routing protocol, there are two major challenges that need to be resolved: (i) Due to broadcast nature of wireless medium, reducing redundant transmission and packet collision is required to conserve energy and improve the communication performance. Thus, selecting candidate nodes for forwarding and assigning a forwarding priority in terms of a forwarding delay become critical; and (ii) In order to have an energy rich node to forward a packet, it is essential to predict the amount of energy available consisting of the remaining energy and the expected harvesting energy. The expected energy consumption of a packet sending or receiving follows a linear equation similar to [10, 38]. However, the expected amount of harvesting energy is directly dependent on the amount of impact force and the distance to the location where the impact is occurred, and thus, unlike to prior work [14, 13, 38], it cannot be modeled independently, e.g. by using a random variable under uniform distribution.

In this paper, we pursue a unified design methodology encompassing the aforementioned design constraints and challenges in a cohesive fashion to realize the proposed routing protocol.

5 Concluding Remarks and Future Work

In this paper, we explored a vibration-based energy harvesting technique and an energy harvesting aware routing protocol in WSNs. In order to characterize the vibration-motivated WSNs, we first developed a simple model of impact spread and an interpolation function for energy conversion. Then we discussed the design constraints and challenges in developing the proposed routing protocol based on the observations. We believe this pioneering study has opened up a new research space in vibration-motivated WSNs and foresee more research to follow up.

For future work, we plan to consider more rigorous mathematical approaches for analyzing vibration-based energy harvesting even though low computational complexity and overhead are our primary concern. Also as a part of designing the proposed routing protocol, tradeoff between communication performance, scalability, and complexity will be investigated. In addition, we plan to implement the proposed routing protocol with a set of sensor nodes, in which each node is equipped with a MSP430 ultra low-power microprocessor [2] and attached with the PFCB W14 to replenish the battery energy. MSP430 IAR C/C++ compiler is used to compile and execute the proposed routing protocol written by mixture of C/C++ and Assembly codes.

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