DESIGN CONSIDERATIONS FOR INTERMITTENTLY CONNECTED ENERGY HARVESTING WIRELESS SENSOR NETWORKS

by

Md Majharul Islam Rajib

A dissertation submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in
Electrical Engineering

Charlotte

2018

Approved by:

Dr. Asis Nasipuri

Dr. Jiang Xie

Dr. Yu Wang

Dr. Srinivas S. Pulugurtha

ABSTRACT

MD MAJHARUL ISLAM RAJIB. Design Considerations for Intermittently Connected Energy Harvesting Wireless Sensor Networks. (Under the direction of DR. ASIS NASIPURI)

Wireless sensor networks can potentially achieve perpetual maintenance-free operation by harnessing ambient energy from the environment. However, most environmental energy sources, such as vibrations, heat, radio frequency (RF) are usually inadequate and sporadic in nature. Therefore, sensor nodes that rely solely on such environmental resources, suffer from frequent and random energy outages. This energy outage leads to intermittent connectivity and induces a large delay in multi-hop transmission paradigms.

The objective of this research is to minimize the end-to-end latency due to this intermittent connectivity. In order to address this problem, several approaches are explored. First, cooperative relaying is investigated as a potential mechanism for reducing the transmission delay. The latency associated with cooperative relaying over unicast routes is analyzed and a novel scheme is proposed to improve the performance of cooperative relaying in a more practical multi-hop setting. Next, a predictive retransmission strategy is developed to find the best retransmission intervals that maximize the success probability associated with each transmission. This strategy is then adapted to two different asynchronous routing protocols: cooperative relaying over unicast routes and opportunistic routing. Finally, the delay characteristics of RF energy harvesting sensor networks is explored and analytical models are formulated to reduce delay by efficiently distributing packet forwarding load between the transmitter and receiver nodes. Performance evaluations from the theoretical models and simulations show that the proposed methods can significantly improve the delay performance in comparison to existing solutions.

ACKNOWLEDGEMENTS

I would like to start by expressing my sincere gratitude to my advisor Prof. Asis Nasipuri, for his immense support and guidance throughout my Ph.D. years. He has helped me to identify key research issues, patiently spent countless hours to discuss and refine my cluttered ideas, and equipped me with the necessary tools to become an independent researcher.

Thanks to my dissertation committee members, Prof. Jiang (Linda) Xie, Prof. Yu Wang, and Prof. Srinivas Pulugurtha for their suggestions and encouragement, and their willingness to squeeze their schedules to accommodate my requests.

I would like to thank my friends: Ji Li, Md Shakawat Hossan, Morium Bably, Yiqian Li, Sayali Nimkar and many other graduate students for all their help. Their company has made my Ph.D. life both fun and rewarding. Thanks also to my family members who have supported me with their encouragement and best wishes.

Finally, special thanks to my wife Wahida Nasrin for her love and patience. For all the time I needed a close friend, a family member, a colleague, or a brain, she was there. I couldn't have done this without her.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

A wireless sensor network (WSN) is a network of many low power, distributed embedded devices that can sense their environment and wirelessly transfer the information to a remote data sink through multi-hop routing. These devices are equipped with low power microcontrollers that can perform basic data processing and implement lightweight wireless protocol stacks. They also have various environmental sensors and a transceiver module for wireless communication. An onboard energy supply such as a primary (non-rechargeable) battery or supercapacitor powers the whole device. Once deployed, these devices autonomously form an ad-hoc network, usually through a tree topology rooted at the sink as illustrated in Fig. 1.1. WSNs offer a low cost, adaptive, and distributed monitoring solution that can be conveniently deployed over wide geographical regions and hard to access places. However, the logistical cost of periodically replacing batteries is the main deterrent for using them for long-term monitoring applications.

1.1 Intermittent Connectivity in Energy Harvesting Paradigm

Finite, single-use onboard energy resources such as batteries in Wireless Sensor Nodes continue to be the key challenge in achieving long-term maintenance-free operation. To address this challenge, earlier research efforts were focused on energy conservation techniques [1, 2] using single-use batteries. This includes optimizing the lowest layer through transmission power control or modulation optimization etc, routing and MAC layer through duty cycling, energy efficient routing strategies, and application layer data aggregation, storage, and adaptive sampling just to name a few. However, long-term sustainability of Wireless Sensor Networks can only be achieved

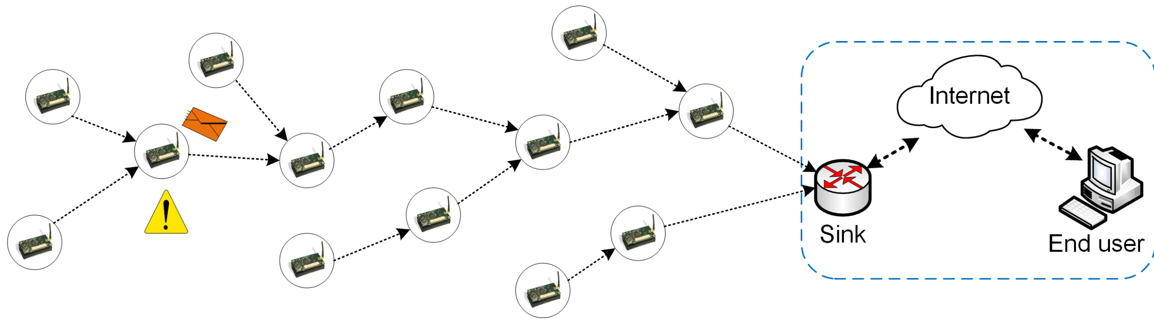

Figure 1.1: A typical sensor network deployed for event monitoring.

if the sensor nodes do not have to rely on batteries. This has triggered wide interest in ambient energy-harvesting technologies for wireless sensor nodes [3–6]. The goal is to achieve a batteryless operation, where nodes harvest energy from the environment and use short-term reliable storages such as super-capacitors or solid state batteries. However, a key problem is that environmental energy sources such as light, mechanical vibrations, radio frequency (RF), heat etc. are highly unpredictable and sporadic in nature [7–9]. In addition, the amount of energy available from these sources is usually limited. In some cases, the available power from environmental harvesting devices may be significantly lower than that required for continuous operations. Examples include vibration energy harvesting and RF energy. The random availability of energy sources coupled with limitations of supply and storage makes it difficult to operate the wireless sensor nodes continuously for extended periods of time. Consequently, sensor nodes in such batteryless WSNs may frequently have to shut down their power-hungry components such as the radio and go into a deep-sleep mode until they recharge up to a certain level to become active again. This gives rise to intermittent connectivity in WSNs, where the wireless nodes experience random and asynchronous outages [10].

Message delivery in such *intermittently connected sensor networks (ICSN)* pose several challenges. First, the asynchronous nature of the sleep-wake periods of the nodes makes it difficult to implement fixed scheduling schemes, which is one of the

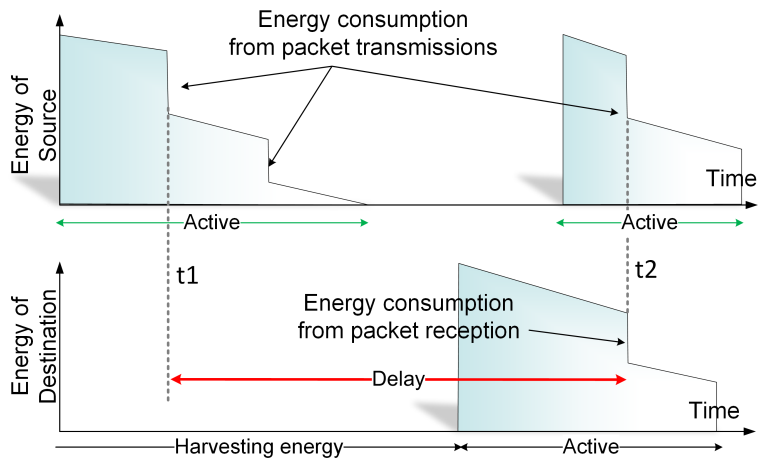

Figure 1.2: Packet forwarding delay in an intermittently connected link.

mechanisms that can be applied for achieving reliable data transfer with limited energy wastage. Second, unlike in non-rechargeable sensor networks where reliability is achieved primarily by extending the battery life using energy conservation methods, here more aggressive communication strategies are required that are closely tied to the characteristics of energy harvesting and consumption in the sensor nodes. This is because of the fact that energy storage devices such as super-capacitors and solid-state batteries have limited storage and high leakage, leading to energy wastage without use. Third, in some scenarios such as RF energy harvesting networks, the amount of harvestable energy is highly correlated to the spatio-temporal property of the node making message forwarding capabilities non-uniform. Consequently, the achievement of low latency communications in ICSNs requires efficient utilization of the active periods of the nodes that depend on the energy arrival and consumption characteristics.

1.2 Research Outline

To better understand the packet forwarding delay in an intermittently connected network, let's consider a link consisting of a single source-destination pair. The energy dynamics of this pair is illustrated in Fig. 1.2. Initially, the source has sufficient energy to perform packet transmission whereas the destination does not have enough energy for the reception and it is in the inactive harvest mode. The source repeatedly attempts to forward a packet but all of its transmission attempts are wasted due to the dormancy of the receiver. Because of the high energy cost of transmissions, the source quickly depletes all of its energy and goes into inactive mode. After a while (usually, this period is long since the energy replenish rate is low), both the source and destination accumulate a certain level of energy and resume their normal operation. This time when the source transmits, the destination can receive the packet, and the packet forwarding is completed. Since the probability that both the source and the destination's active periods overlap is very low in an intermittently connected network, the delay involved in forwarding a packet is significantly large.

In this research, we concentrate on the design considerations for reducing delay in ICSNs. Specifically, we develop strategies for MAC and routing layers to benefit from the energy harvesting characteristics and reduce the end-to-end latency over multi-hop routes. Two types of ICSNs are considered. In the first type, nodes experience independent and identically distributed random energy outages due to randomness (mostly uncorrelated) in their energy arrival. Examples of such ICSNs are where nodes harvest energy from vibrations caused by passing vehicles [9] or piezoelectric stress generated from human footsteps [11]. The second type of ICSNs where the energy outages in the nodes are relatively predictable but have a very high spatial correlation. RF energy harvesting networks which are attracting increasing attention, fall in this category [12]. Our design approaches to minimize delay in these ICSNs are discussed below,

- **Delay minimization through transmit time diversity:** In ICSN, each node goes through random periods of active and deep-sleep cycles. When a node blindly tries to forward a packet i.e., without any knowledge of the active state of the receiver, it can enhance the success probability by increasing and spreading out the total number of delivery attempts. Since energy harvesting is limited, the number of attempts can only be increased with the help of other nodes by either increasing the number of sources independently trying to forward the same packet or by increasing the number of independent potential receivers willing to receive the same packets. The randomness of active periods in these additional nodes will automatically spread out the attempts. We leverage these concepts to minimize the link delay with cooperative relaying over unicast routes and opportunistic routing. In cooperative relaying, when a node's transmission attempt fails to reach the desired destination, and a common neighbor (neighbor to both source and destination nodes) node overhears the packet, it offers to cooperate by independently forwarding the packet on behalf of the source node. Cooperative relaying improves energy utilization by tapping into the energy resources of idle nodes in the vicinity of the source and destination, some of this energy would otherwise be wasted due to ambient processes, such as overhearing or leakage. Opportunistic routing is the process by which any node that receives a packet attempts to forward it to another node that is closer to the destination. As discussed in the next chapter, opportunistic routing has received considerably more attention in the literature compared to unicast routing with cooperative relaying. Hence, we first develop a stochastic model to quantify the performance improvement achievable from cooperative relaying. Then, we propose a cooperative relaying based two-hop routing protocol that further minimizes the delay in a multi-hop network.

- **Delay minimization through predictive retransmission interval:** The harvest rates in ICSNs are usually minuscule, and therefore, the deep-sleep phases (for harvesting energy) are long and can significantly affect the overall delay performance. After each deep-sleep phase, the source nodes wake up to make a handful transmissions attempts with the limited amount of energy they harvested. If the success probabilities from these attempts are low, they again have to go through the long deep-sleep mode and wait for the next set of attempts. In this research, we increase the success probability of each attempt by optimizing the retransmission interval, and consequently, reduce the number of long futile waiting periods. The idea is to *predict the best time for a retransmission* after each failed transmission that maximizes the probability of successfully reaching a destination. We recognize this as an important parameter since the optimum retransmission interval can potentially minimize energy wastage caused by unsuccessful retransmissions that increases with excessively small retransmission intervals at the same time reducing the probability of missing the active window of the receiver, which eventually leads to a longer average delay. We present a probabilistic model to find this optimal packet retransmission times. Our prediction strategy is based on the energy arrival rate as well as node's activities such as transmission, reception, and sensing to reflect the real-life scenario. We also develop a mathematical formulation to estimate the expected delay and use simulations to evaluate the delay characteristics of the proposed model. Finally, we integrate this predictive schemes in both unicast routing with cooperative relaying and opportunistic routing protocols to minimize the end-to-end latency.

- **Delay minimization by parent assisted data transmission process:** IC-SNs where RF energy harvesting is the principal mean for energy supply, exhibits a unique property- node's energy harvest rate is highly dependent on the proximity to the RF energy source [13, 14]. Often this RF energy source is located at the sink which makes the parent nodes significantly more capable of handling traffic (transmission and reception) compared to their children. This is rather desirable since parents not only have to forward its own traffic but also children's traffic as well. Interestingly, our study shows that the amount of energy children have to spend for forwarding packet is much higher than its par-

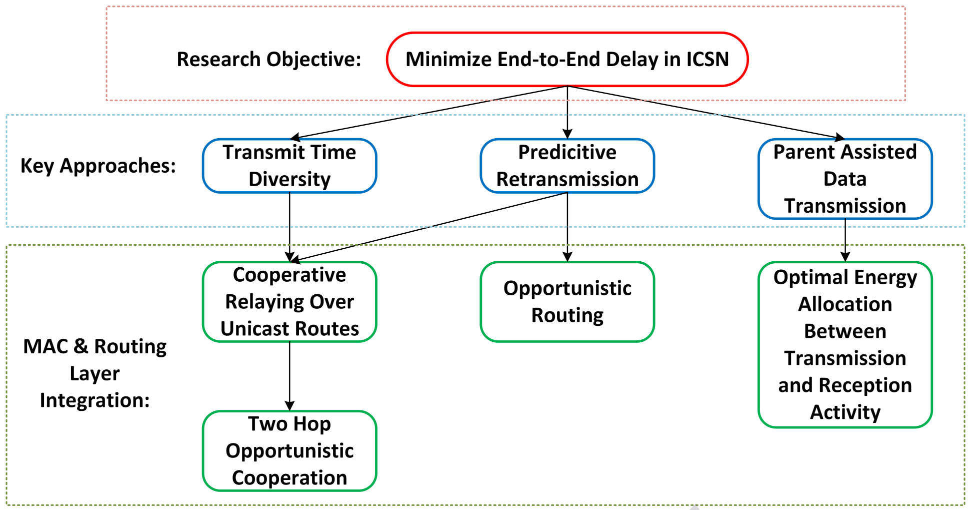

Figure 1.3: Research outline.

ent. This high energy cost combined with lower harvest rate makes children's traffic more susceptible to a longer delay. This becomes severe as the child's distance increase from the sink and causes a bottleneck in the multihop packet flow. Compared to traditional sensor network where the usual bottleneck is near the sink [15], the bottleneck here is shifted towards the periphery of the network. In this research, we address this unique issue by effectively offloading some of the child's packet forwarding burden to the parent. We first compare the performance of transmitter-initiated versus receiver-initiated transmissions and show that the parent initiated process has a comparatively lower average delay, which is to the fact that the parent (in this case receiver) can take away some of the load from the children by initiating the transmission and reduce link delay of the child. Next, we allow a parent to further assist its child by optimally allocating its harvesting energy among transmission and reception activities, i.e., packet forwarding to the next parent and packet reception from its child. Extensive numerical results are presented to provide an insight into the upper bound characteristics of link throughput and optimal energy distribution strategy of the parent.

A summary of these key design considerations are illustrated in Fig. 1.3.

1.3 Organization of the Dissertation

The rest of the thesis is organized as follows. Chapter 2 discusses related works. In Chapter 3, we introduce cooperative relaying over unicast routes and propose an enhanced two-hop relaying protocol. The predictive retransmission strategy is discussed in Chapter 4. A load distribution method for RF energy harvesting networks is discussed in Chapter 5. We summarize our contributions in Chapter 6 followed by recommendations for future work.

CHAPTER 2: RELATED WORK

Over the past decade, a large number of MAC [16–21] and routing [22–26] protocols have been proposed to efficiently deliver a packet from the source to the sink in multihop WSNs. However, most of these schemes are suitable for specific WSN scenarios and do a trade-off between energy budget, throughput, QoS, delay, and simplicity. In the first part of this chapter, we present a brief overview of the energy harvesting technologies. In the second part, we provide some of the MAC and routing layer protocols that are predominantly used in energy harvesting ICSNs for reducing the end-to-end transmission delay.

2.1 Energy Harvesting in Wireless Sensor Networks

Demand for long-lasting maintenance-free sensor network applications, the feasibility of deployment in potentially hazardous or sensitive monitoring applications, and scenarios with limited accessibility to nodes such as deeply embedded sensor networks have driven the research community to come up with alternate energy solutions to the onboard single-use batteries. In the recent years, tapping into the ambient energy sources such as solar, vibrations, thermal, etc. [6, 7, 27–30] as an alternative solution to the primary batteries has gained immense attention. In the following, we briefly discuss some of the popular energy sources used for powering sensor networks.

- Photovoltatic: Harnessing energy from the light sources by leveraging the photoelectric effect is one of the most mature technology for energy harvesting. It is simple, cheap, and easy way to convert ambient energy for the sensor devices because of the abundance of outdoor sunlight and adequate indoor lighting in many places. The amount of surface area for capturing light and illumination level determine how much energy can be harvested. Typically it varies from 100 to 400 mW for approximately 4 to 10 $inch^2$ surface area for harvesting (Helimote [31], Hydrowatch [32], SolarBiscuit [3], Prometheus [4]), which is pretty good compared to other energy sources. However, the complete unavailability of the solar source during the night and supply fluctuations due to the weather and season change require careful system design with sufficient storage capacity and long inoperability (for example, sleeping during the night). Also in many applications such as structural health monitoring and indoor sensing for smart homes etc., photovoltaic energy harvesting is not feasible due to the insufficient exposure to light.

- Piezoelectric: When external strain (usually through vibration or motion) is applied to the piezoelectric materials, it deforms their structure and generates potential. This energy can be generally harvested without the requirement of multistage processing to get necessary voltage levels. An extensive review of vibration energy harvest leveraging piezoelectric effect can be found here [29]. Vibrations generated from road traffic [9], factory machines [33], sound waves etc. are popular energy sources for piezoelectric harvesting. Furthermore, human motions such as footsteps [34, 35] or push-buttons [36] are also explored as the source of energy. The amount of energy that can be harvested using piezoelectric effect is largely correlated to the energy source characteristics and the piezoelectric material properties. For instance, it can be observed in [9] that there is a noticeable spike in traffic-induced vibration energy harvesting whenever a vehicle crosses over the bridge. Typical harvest amount is 100 $\mu W/cm^3$ for vibration harvesters and 20 to 80 mW peak power for footstep harvesters [7].

- Thermoelectric: In this type of harvesting, thermal energy is converted to electricity by utilizing the Seebeck effect. One end of the Thermoelectric generator has to be in contact with the heat source and the other end to a colder source. Some potential energy sources for thermal energy harvesting are human bodies [37, 38], room heater [39], CPU heatsinks [40] etc. The harvester characteristics are quite reliable and have long operational life, however, the harvesting efficiency is usually very low resulting in inadequate energy harvest (in the range of 0.5 $\mu W/mm^3$).

- Flow based: Airflow based harvesters typically deploy micro wind turbines to harvest energy from the wind flow through frequency voltage converters [41, 42]. However, the sensor node harvester combination is typically larger compared to other setups, and energy harvest amount greatly varies with the wind speed, direction, and obstructions. Another popular choice for flow-based harvesting is hydropower where the kinetic energy of the moving or falling liquid such as water is converted into the electricity [6]. Approximately 20 mW constant energy supply can be obtained using a commercial harvester as shown in [43].

Besides the aforementioned harvesting techniques, the RF energy harvesting is gaining more momentum recently. Therefore, we mention the details of the RF energy harvesting schemes in a separate section in the following.

2.1.1 RF Energy Harvesting

RF energy harvesting is a process of harnessing energy from the far-field electromagnetic radiation in the RF band. Usually, this band ranges from 3 KHz to 300 GHz. However, most of the energy harvesting research activities are focused on TV [12], Cellular [44, 45], and ISM [46–48] bands. RF transmission (that may or may not contain information) is captured by the harvesting device's antenna. In contrast to the regular radio receiver, however, here the energy receiving circuit has an RF to DC conversion channel for transferring incident energy at the antenna to a storage device for energy accumulation. Capturing energy and information at the same time is also possible using power splitters or time-sharing mechanisms. This is known as simultaneous wireless power and information transfer (SWIPT) [49].

There are two types of RF energy sources [14], namely, i) ambient sources [44, 50]: these are already existing RF transmitters that are meant for domestic appliances such as TV, Bluetooth, WiFi, cellular transmissions, etc. and operates within 0.2 GHz to 2.4 GHz band, ii) dedicated sources [51, 52]: on-demand energy transmitters that usually operate in ISM bands with possibly narrow directional and high gain antennas. Usually, the received power density from ambient sources are extremely low but facilitates costless energy. On the other hand, dedicated energy sources can be leveraged for applications that have latency and throughput requirements.

In general, wireless energy transfer can be broadly categorized [8] into three groups– mechanical waves, magnetic fields, and electromagnetic radiations. RF energy harvesting falls under the larger category of electromagnetic radiations. A brief description of all three is provided below so that the reader can easily distinguish RF harvesting from the other two.

- Mechanical waves: mechanical waves propagate by generating oscillations (compression and expansion) in the media and transfer kinetic energy from one place to another. These oscillations cause vibrations in the receiving elements, thus facilitating vibrational energy harvesting. Among others, energy transfer via acoustic wave is the most commonly researched and easiest to implement technology. However, its efficiency and range are greatly affected by the propagation media.

- Magnetic fields: this method mainly utilizes magnetic fields and its electromagnetic phenomenon. Two transfer mechanisms are primarily used: inductive coupling and resonant inductive coupling. In inductive coupling, two magnetically coupled coils are deployed. By applying alternating current at the transmitter coil, the magnetic field inside the coupled receiver coil can be changed, which generates the potential. This is suitable for near-field (in the cm scale) high-efficiency energy transfer applications. For inductive resonant coupling, a capacitance is added to each coil to form a tuned LC circuit. It is possible to attain high efficiency over a greater range relative to the coil's diameter by resonating both coils at a common frequency.

- Electromagnetic radiations: here energy carried in the electromagnetic waves are converted to electrical energy using antennas. Specialize antennas are included in both transmitter and receiver for high gain and narrow directivity. Energy can be steered towards various points using beam-forming, and transmitted up to several kilometers. In order to transfer energy more efficiently, low frequencies can be used for their lower path loss. However, lower frequencies require larger antennas which may not suit the smaller form factors of the network nodes. Furthermore, to avoid interfering other signals or minimize health hazards, government regulations restrict the transmission power. Therefore, careful design considerations for efficient energy transfer is necessary.

RF harvesting can be a great solution for future WSNs since, i) a large number of devices spread over a region can be easily powered ii) energy source and the harvester is spatially decoupled iii) energy can be harvested from the already existing ambient RF environment iv) harvested energy is usually stable, predictable and sometimes controllable. However, there are also some drawbacks such as i) very low harvest rate and high spatial correlation ii) energy reception sensitivity has to be higher compared to information reception iii) additional harvesting circuitry and power management is necessary.