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# Energy neutral directed diffusion for energy harvesting wireless sensor networks

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ABSTRACT

In recent years, energy harvesting techniques have been used to mitigate the problem of the energy resource limitation in traditional Wireless Sensor Networks. In particular, it is now possible for a sensor with energy harvesting capabilities to operate perpetually in an *Energy Neutral* state, which can be achieved by making sure that the harvested energy will be able to replenish the energy that is being consumed. In this paper, we propose a query driven Energy Neutral Directed Diffusion (ENDD) protocol that aims at maintaining the network level energy neutral state, which in turn provides consistent data delivery and unlimited network lifetime. Traffic flow admission controls are carried out locally at each sensor based on their own energy harvesting status, which prevent sensors from shutting down due to excessive usage of energy. We also propose a real-time realistic energy consumption estimation model to improve the reliability of the admission control process. Furthermore, we analytically show that ENDD is highly scalable as it is able to guarantee a linear upper bound on the total number of communication control messages exchanged for route establishment. Extensive simulations are also carried out to evaluate and compare the performance of our proposed ENDD protocol against other query driven routing protocols.



## 1. Introduction

Powered by small batteries/supercapacitors, one of the biggest problems faced by traditional Wireless Sensor Network (WSN) is the limited energy resource. A sensor will be *dead* when the energy resource stored in its battery is depleted. As a dead sensor cannot perform any kind of tasks, the performance of the WSN will degrade severely when one or more sensors are dead. Thus, the *Network Lifetime*, which is measured by the amount of time elapsed before the first sensor node is dead, is used as an important performance metric for traditional WSNs.

As the amount of data traffic carried by a sensor node will directly determine its energy consumption, the lifetime of a network can be extended by using energy efficient network layer routing protocols. Based on different data delivery models, routing protocols can be classified into three categories: *Continuous*, *Query Driven* and *Hybrid* Model [1].

Using the continuous model (such as the ones in [2,3]), data information sensed by sensors will be delivered to the destinations periodically with a specific data packet transmission rate. Using the query driven model (such as Directed Diffusion [4]), the transmission of data will be triggered only when a query is generated by the user. The Hybrid Model is the combination of continuous model and query driven model [5]. We note that using the query driven model, only data queried by the user will be sensed and then delivered to the destination. Hence, less data will be transmitted when the query driven model is employed as compared to the continuous model. This in turn implies that the query driven model is highly energy efficient and thus has the potential of providing longer network lifetime. Energy aware query driven routing protocols [6,7] have also been proposed to further extend the lifetime of the network. However, no matter how energy efficient these routing protocols are, sensors will eventually deplete their batteries and stop functioning, which results in inevitable network failure.

With the emergence of energy harvesting techniques, wireless sensor nodes are equipped with energy harvesting devices so that additional energy can be harvested from the ambient environment. We refer to this kind of sensor node as the *Energy Harvesting Sensor* (EH-Sensor). With the energy harvesting technology, it is now possible for an EH-Sensor to operate perpetually in an energy neutral state. This *Energy Neutral* state can be achieved when an EH-Sensor

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consumes no more energy than that it can harvest in a certain period of time [8]. We refer to a wireless sensor network that consists of only EH-Sensors as the *Energy Harvesting Wireless Sensor Network* (EH-WSN). By maintaining every EH-Sensor in the network in the energy neutral state, it is now possible for an EH-WSN to operate perpetually with unlimited lifetime.

Thus, the research interest has been recently shifted from the energy aware routing to *Energy Harvesting Aware* routing. Several energy harvesting aware routing protocols (such as the ones in [9–11]) that are based on the continuous data delivery model have been proposed in the literature. However, to the best of our knowledge, there has not been any work on energy harvesting aware routing protocols that are based on the query driven data delivery model. Due to the inherited high energy efficiency, a query driven routing protocol has the potential of further enhancing the performance of a sensor network with energy harvesting capabilities. In view of this, we study in this paper a query driven routing protocol that aims at providing energy neutral operation for an EH-WSN. This protocol can improve the end to end data transmission reliability while providing unlimited network lifetime, which is highly desired for applications such as target tracking and surveillance [12,13].

The main contributions of this paper are:

- A query driven Energy Neutral Directed Diffusion (ENDD) routing protocol. Admission controls are carried out locally at each node based on its energy harvesting status to admit or reject data traffic routing requests. Using ENDD, the network level energy neutral state can be achieved, which provides unlimited network lifetime and consistent network service.
- A realistic energy consumption estimation model to improve the accuracy of the admission control procedure, which in turn enhances the reliability of the sensor energy neutral state guarantee.
- Analytically derived upper bound on the amount of control messages exchanged for route establishment. This upper bound has a linear relationship with the network size, which means ENDD scales well with the network size.

The rest of the paper is organized as follows. Previous related works are reviewed in Section 2. Section 3 contains the system models and notations we use. Operations of our proposed ENDD protocol are presented in Section 4. Empirical studies are carried out in Section 5 to evaluate the performance of our proposed ENDD protocol. The paper will conclude in Section 6.

## 2. Related works

### 2.1. Energy harvesting aware routing protocols

In recent years, several continuous data delivery model based energy harvesting aware protocols have been proposed. Lin et al. presented the Energy-opportunistic Weighted Minimum Energy (E-WME) [9] routing protocol which assigns each energy harvesting sensor with a cost that is related to the energy harvesting rate and then calculate the shortest path according to each node's cost. The Randomized Minimum Path Recovery Time (R-MPRT) routing protocol [10] proposed by Lattanzi et al. assigns a cost to each edge that is related to the energy required to transmit a packet and the energy harvesting rate. Hasenfratz et al. compared in [11] the above two protocols and found that if we calculate the cost in R-MPRT with respect to the available energy instead of the energy harvesting rate, its performance will be better than that of E-WME. These routing protocols determine the appropriate routing path by considering the battery residual energy and the energy harvesting rate. In this way, the network traffic can be routed on energy harvesting sensors that have better energy status. In [14], a multiple path routing protocol is proposed to improve the data collection quality and the routing sustainability in an energy harvesting wireless sensor network. A power generation pattern based routing protocol is proposed in [15] to improve the packet delivery ratio. In [16], the transmission quality, energy consumption and energy wastage are considered to improve the energy efficiency of the routing protocol designed for energy harvesting WSN. There are also energy harvesting aware hierarchical routing and clustering protocols [17–19] that choose sensors with better energy harvesting status to act as cluster head to carry heavy network traffic.

A joint energy management and routing protocol has been proposed in [20] to compute the optimal routes so that the overall data transmission capacity at all energy harvesting sensors can be maximized while maintaining the energy neutrality of all the energy harvesting sensors. The proposed maximization problem is solved by using dual decomposition method and a distributive implementation of the method is proposed for a network with a special structure, namely the directed acyclic network graph (DAG). In a more recent research [21], a cross layer routing protocol is proposed while taking both MAC layer and network routing layer into consideration. With this kind of design, energy savings can be achieved by dynamically adjusting the duty cycle of the sensors according to the traffic load.

### 2.2. Query driven routing protocols

In the literature, Directed Diffusion (DD) [4] is an important query driven based routing protocol for traditional wireless sensor networks. It uses a publish and subscribe mechanism to efficiently pull desired data information. In order to create a query, *Interest* packets will be generated at the sink(s). These interests will diffuse across the network to find the sensor nodes that have sensed the desired information.

The original Directed Diffusion proposed in [4] uses a *Two Phase Pull Diffusion* (TPPD) model. In the first phase, interests will be diffusing across the network to pull down low quality information from the data source. Upon receiving these interests, the data source will send back the queried low quality information in the form of data packets (with a very low packet transmission rate), which are referred to as the *Exploratory Data Packets* (EDPs). The second phase begins once the sink receives these EDPs and it will send out reinforcement interests to pull down high quality information. The high quality information (in the form of data packets with a high packet transmission rate) will be sent back to the sink via the *Empirically Lowest Delay Path*, which is consists of sensors that delivers the EDPs with the lowest empirical delay.

In [22], an *One Phase Pull Diffusion* (OPPD) model is proposed to extend the original DD protocol. Using this model, hops count will be recorded by the sensor when the interests are diffusing in the network. Once these interests are received by the data sources, they will directly send back data packets with a high data packet transmission rate. These data packets are routed to the sink via the sensors that have lower hops count to the sink. Since no reinforcements or exploratory data packets are needed, the One Phase Pull Diffusion model has a lower control message overhead as compared with the Two Phase Pull Diffusion model. However, as indicated in [6], the low delay path established by using hops counts (instead of the empirical delays) might not be the lowest delay path. Thus, higher end-to-end data delivery delays might be experienced using OPPD model as compared to TPPD model.

Since the original and the modified version of DD always choose the low delay path to carry traffic flows, sensors along this path will die faster than the rest of the sensors. This will in turn result