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Energy neutral clustering for energy harvesting wireless sensors networks

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ABSTRACT

For wireless sensor networks with energy harvesting capabilities, it is possible to achieve perpetual network operation by maintaining every sensor in the network in an Energy Neutral state. In this paper, a distributive Energy Neutral Clustering (ENC) protocol is proposed to group the network into several clusters, with the goal of providing perpetual network operation. ENC employs a novel Cluster Head Group (CHG) mechanism that allows a cluster to use multiple cluster heads to share heavy traffic load. This CHG mechanism can help to reduce the frequency of cluster re-formations, which in turn reduces the control message overhead. The optimum number of clusters that maximizes the amount of information gathered from the network is mathematically derived using convex optimization techniques. Based on this optimum number of clusters, an extension to ENC is proposed to group the network into equal sized clusters so that maximized network information gathering can be achieved. Extensive empirical studies show that our proposed protocol can successfully prevent sensors from shutting down due to the excessive usage of energy, which in turn provides perpetual network operation with consistent data delivery. Substantial improvements on the amount of information gathered from the network can also be achieved by using our proposed protocol as compared to traditional clustering protocols.

1. Introduction

Wireless sensors are widely used in applications such as field monitoring and target tracking [1]. These sensors can gather information sensed from the ambient environment and transmit/receive information to/from neighboring sensors. By forming networks using large amount of sensors, information gathered by these sensors can be routed to one or more destinations to be further analysed.

Powered by batteries/supercapacitors, traditional wireless sensors have only access to limited energy resource. Since these wireless sensors are usually deployed in a large area and some of them are dangerous to reach, it is difficult and costly to replace their batteries [2]. Thus, a sensor will be *Dead* when the energy resource in its battery is depleted and it will stop functioning. Since a dead sensor cannot sense or relay information anymore, network performance levels, such as the network throughput, will degrade when one or more sensors in the network are dead. Thus, mechanisms to prolong the *Network Lifetime*, which measures the amount of time elapsed before the first sensor (or a fraction of sensors) is dead, are being extensively studied in the past few decades.

Since the routing of data packets directly determines the energy consumption for a sensor, many network layer routing protocols [3] have been proposed to efficiently

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utilize the available energy to prolong network lifetime. One category of these routing protocols is the clustering protocols ([4]) that group sensors in the network into a number of clusters. In each cluster, there will be a Cluster Head and several Cluster Members. A *Cluster Member* (CM) is the type of sensor that senses information from the environment and then sends the sensed information to the Cluster Head for further processing. The *Cluster Head* (CH) gathers and aggregates the information sent by the CMs. It will then send the aggregated information to the Base Station. By efficiently managing the selection of the CH and CMs, several clustering protocols (such as the ones in [5–7]) have been proposed to prolong the network lifetime. However, due to the limited energy resources available in the batteries, no matter how carefully these clustering protocols are designed, sensors will eventually deplete their batteries and stop functioning.

With the emergence of energy harvesting techniques, wireless sensors are equipped with energy harvesting devices (such as solar panel or thermal energy harvester), to gain access to additional energy resource harvested from the ambient environment. We refer to this kind of sensor as the *Energy Harvesting Sensor* (EH-Sensor) and we refer to the network formed solely by EH-Sensors as the *Energy Harvesting Wireless Sensor Network* (EH-WSN). For EH-WSN, the term network lifetime is no longer a primary concern. Dead sensors will resume operation when sufficient energy has been harvested by their energy harvesting devices. As a matter of fact, for an EH-Sensor, an *Energy Neutral* [8] state can be achieved, (when the energy used by a sensor is less than the amount of energy harvested), so that it can operate perpetually with desired performance level (subject to hardware failure). This kind energy neutral operation offers a great potential in building a robust network with infinite lifetime.

Several flat routing protocols ([9–11]) have been proposed in the literature to provide network-wide energy neutral operation. However, to the best of our knowledge, clustering protocol that aims at providing perpetual operations for an EH-WSN has not been explored. As compared to flat routing protocols, clustering protocols possess the inherited advantages on energy efficiency and scalability [4]. Thus, we study in this paper the way to cluster an EH-WSN so that every sensor in the network can achieve energy neutral state and operate perpetually. The main contributions of this paper are:

- An Energy Neutral Clustering (ENC) protocol that ensures the network-wide energy neutral operation. ENC clusters the network with goal of providing perpetual network operation by controlling the size of the clusters as well as the data traffic load at each sensor. It can be implement distributively with a low protocol communication overhead.
- A Cluster Head Group (CHG) mechanism that allows one cluster to have multiple Cluster Heads. CHG helps reduce the number of cluster re-formations and Cluster Head re-selections needed. This in turn reduces the protocol control message overhead and enhances the consistency of data delivery.
- Mathematically derived optimum number of clusters that maximizes the amount of information that can be gathered from the network while maintaining network wide energy neutral operation.

The rest of the paper is organized as follows. In the next section, we review some of the important works that are related to our proposed protocols. Section 3 discusses the network topology as well as the energy model we use. Our proposed ENC protocol will be presented in Section 4. The optimum number of clusters that maximizes the data information gathering is derived in Section 5. An extension to ENC is proposed in Section 6. Empirical studies that verify the performance of our proposed protocols are presented in Section 7. The paper will then conclude in Section 8.

2. Related works

In the literature, clustering protocols have been extensively studied in the past few decades. The Low Energy Adaptive Clustering Hierarchy (LEACH) [5] is an important clustering protocol that aims at prolonging the network lifetime. It points out that since a Cluster Head (CH) usually carries heavy processing tasks and traffic loads, it is more energy intensive as compared to Cluster Members (CMs). To address this problem, a *Cluster Head Reselection* (CH-Reselection) mechanism is included in LEACH. The system time is divided into *rounds* and the sensor network will be re-organised into new clusters at the beginning of each round. Sensors that have never been the CH before will have a higher chance of being selected as CHs for these newly formed clusters. Using this kind of CH-Reselection mechanism, energy consumption can be balanced among CHs and CMs and the network lifetime is thus improved.

However, one problem for LEACH is that the CHs that are further away from the Base Station usually consumes more energy than the ones that are nearer to the Base Station. This in turn creates another form of imbalance in energy consumption. Thus, an Energy Efficient Cluster Scheme is proposed in [12] to solve this problem by allocating more CMs to those clusters that are nearer to the Base Station and less CMs to those clusters that are further away from the Base Station.

Another issue is that LEACH assumes that all the CHs in the network communicate directly with the Base Station. The cost for this kind of single hop communication can be very expensive when the distance between the CH and the Base Station is large. In [6], a Hybrid Energy Efficient Distributed (HEED) clustering protocol is proposed to address this problem by adopting a multihop inter-cluster communication model. Using this model, CHs that are closer to the Base Station will relay the information sent from CHs that are further away from the Base Station. Several other protocols are also proposed based on the multi-hop inter-cluster communication model [13–15]. In this way, the expensive long distance communication will be replaced by several less-expensive short distance communications. However, by using these protocols that adopts the multi-hop inter-cluster communication model, CHs