Journal of Network and Computer Applications 35 (2012) 1277–1284

Contents lists available at SciVerse ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Using a dynamic backbone for efficient data delivery in solar-powered WSNs

Dong Kun Noh [a], Junbeom Hur [b],*

[a] School of Electronic Engineering, Soongsil University, 369 Sangdo-ro, Dongjak-gu, Seoul 56-743, Republic of Korea
[b] School of Computer Science and Engineering, Chung-Ang University, 84 Heukseokro, Dongjak-gu, Seoul 156-756, Republic of Korea

ARTICLE INFO

Article history:
Received 19 July 2011
Received in revised form
16 November 2011
Accepted 25 January 2012
Available online 2 February 2012

Keywords:
Solar-powered
Sensor network
Topology control
Low-latency
Energy consumption
Network performance

ABSTRACT

The periodic nature of solar power requires a different approach to energy consumption in wireless sensor networks (WSNs) from battery-based WSNs. Based on the energy model of a solar-powered node, we develop efficient energy-aware topology-control and routing schemes which utilize a backbone network consisting of energy-rich nodes within the WSN. This backbone handles most of the traffic with low latency, while reconfiguring itself dynamically in response to changes in the availability of energy at each node. Simulation results demonstrate that our schemes can achieve a balance between latency and energy consumption.

1. Introduction

In battery-powered wireless sensor networks (WSNs), it is not possible to focus exclusively on achieving a specific network-wide performance, to meet targets for throughput or latency, because this will shorten the network lifetime. Desirable levels of throughput or latency must be traded against energy in the batteries of the nodes. Therefore, the design of battery-based WSNs is usually focused on minimizing energy consumption in order to prolong the network lifetime.

Recently, however, environmental energy has emerged as a feasible supplement to battery power for wireless sensor systems deployed where manual recharging or replacement of batteries is not practical. The most popular source of environmental energy for WSNs is the sun. Solar energy is of course intermittent, but provides a high power density of about 15 mW/cm^3). This periodic availability of a high recharging power makes it feasible for wireless sensor nodes to operate in a way which enhances network-wide performance, instead of being focused on minimizing energy consumption. In this paper, we show how latency and energy consumption can be balanced across a network.

We have designed a distributed and localized topology control algorithm which is periodically invoked in each node of a WSN, and which chooses the transmission power of the node, allowing it to adapt to the amount of available energy. This adaptive topology control algorithm for solar-powered nodes, which is called SolarTC, has the following properties:

- *Energy-adaptive operation*: SolarTC makes each node operate in an energy-saving (ES) mode, if the node is short of residual energy. In this mode, a node tries to maintain the minimum transmission power level needed to preserve the marginal connectivity of the WSN, while saving energy so as to minimize blackout time. Otherwise, the node operates in an energy-rich (ER) mode, and tries to construct an ER-backbone network consisting of fellow ER-nodes. To increase the robustness of this backbone, an ER-node increases its transmission power so as to find as many ER-neighbors as possible.
- *Minimizing the disadvantage of existing topology control techniques in achieving low latency*: Basically, existing topology control schemes achieve low latency by increasing the transmission power (and hence the range) of each node. But this increases MAC-layer contention and thus reduces the network capacity. In SolarTC, however, only ER-nodes (not all nodes) increase transmission range, which reduces the extent of the contention.
- *Maintaining a stable backbone network*: When there is a lot of sunlight, most nodes go into ER-mode, so the ER-backbone network stays connected and robust. However when there is insufficient sunlight, the ER-backbone network may become disconnected and unstable. SolarTC tries to solve this problem by having some ER-nodes work in ES-mode to save energy, allowing them to operate later in ER-mode when most nodes are in ES-mode.
- *Supporting low-latency and energy-aware routing*: An ER-backbone provides as many low-latency and energy-rich paths as

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* Corresponding author. Tel.: +82 2 820 5302; fax: +82 2 820 5301.
E-mail addresses: dnoh@ssu.ac.kr (D.K. Noh), jbhur@cau.ac.kr (J. Hur).

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doi:10.1016/j.jnca.2012.01.012

possible from ER-nodes to the sink node. Therefore, low-latency routing or energy-aware routing can be effectively implemented on the ER-backbone.

Our final goal is to design an efficient routing scheme, which can achieve a balance between latency and energy-consumption using an ER-backbone constructed by SolarTC. This scheme is called ER-backbone-based geographic routing (ERB-GR), and it has the following characteristics:

- *Low-latency routing within an ER-backbone*: The ER-nodes which form an ER-backbone network have a higher transmission power than ES-nodes. Therefore, the average hop count along a route from a node to a sink on ER-backbone is less than that for the same journey over the original topology. ERB-GR routes data along the ER-backbone to reduce latency. ERB-GR also considers the duty-cycle of each node, which is the proportion of time for which it is active. This is important in energy-harvesting WSNs which have a low duty-cycle, due to the intermittent availability of environmental energy.
- *Low-energy-consumption routing on ES-nodes*: To extend the duty-cycle of the node so as to maximize the amount of data acquired, each ES-node should use as little energy as possible in routing data. Therefore, when ERB-GR is running on an ES-node, it routes the data to the ER-backbone in an energy-efficient manner.
- *Energy balance among nodes*: ERB-GR routes most of the sensory data to the sink via ER-nodes which have enough extra energy to transfer data. This allows ES-nodes to save energy. The set of ER-nodes which make up the ER-backbone is modified over time, as it adapts to changing amounts of residual energy at each node.
- *Guaranteed delivery*: Even though the ER-backbone is not connected, ERB-GR will deliver data reliably to the sink as long as the network as a whole remains connected. Since the first step in our topology control is to construct a connected network, ERB-GR can always provide guaranteed delivery.

The rest of this paper is organized as follows. In the next section we explain existing topology control schemes and routing schemes for Solar-powered WSNs. Section 3 explains a simple but efficient solar-energy model, which is used by SolarTC described in Section 4. Section 5 explains ERB-GR, which operates in a network constructed by SolarTC. We then evaluate the performance of our scheme in Section 6, and draw conclusions in Section 7.

2. Background

2.1. Effects of topology control in WSNs

Topology control creates and maintains a list of the immediate neighbors of a node in a network. It is related to both routing and the MAC (medium access control) layer in the protocol stack, as shown in Fig. 1. Topology control can trigger a route update when it detects that the list of neighbors of the node on which it is running has changed substantially. By doing this, instead of passively waiting for the routing protocol to update each route separately, topology control provides the routing layer with a faster response to topology changes and a reduced packet-loss rate. Conversely, the routing layer will trigger execution of topology control if it detects many broken routes in the network. The presence of broken routes indicates that the network topology has changed substantially since the last execution of topology control.

Topology control also determines the transmission range of the node on which it is running. The transmission ranges of all nodes determine the expected contention in the MAC layer. Thus, the efficiency of topology control directly affects that of the MAC layer. Conversely, the MAC layer can trigger execution of topology control if it discovers new neighbors by overhearing network traffic.

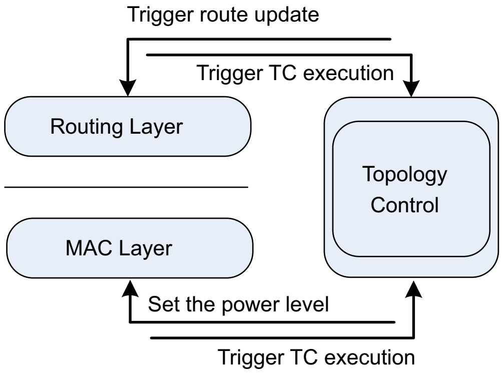

Fig. 1. Interactions between topology control and the routing/MAC layer.

Since the effectiveness of topology control is closely related to the performance of the routing and MAC layers as described above, it is one of the most important issues in designing efficient WSNs. The use of topology control to enhance the overall performance of WSNs has been studied (Santi, 2005; Li et al., 2003; Ramanathan and Rosales-Hain, 2000), but not for the special case of solar-powered WSNs.

2.2. Routing in energy-harvesting WSNs

In the literature, most studies of energy-aware routing focus on residual battery status and do not take into account the environmental energy availability at the nodes. Willig et al. (2002) were the first to develop a routing protocol for nodes with a renewable power supply. Although a lot of work has subsequently been put into the design and development of solar-powered sensor nodes, only a few makeshift topologies and routing protocols have been implemented.

At a time when energy-harvesting techniques were less effective, there was some research (Voigt et al., 2003, 2004) on integrating a small number of solar-powered nodes into an otherwise battery-powered sensor network. The well-known routing protocols, LEACH (Heinzelman) and Directed Diffusion (Intanagonwiwat et al., 2000), were modified to prolong network activity by placing heavier workloads on these additional energy-harvesting nodes.

The first serious attempt to utilize environmental energy for routing (Kansal and Srivastava, 2003) demonstrated that environmentally aware decisions improve performance compared to decisions based only on battery status, although the application scenario was limited. Then, in the Heliomote (Kansal et al., 2007) project, perpetuity of operation was considered in the context of task management, network topology and the routing protocol. The UCLA team's implementation of a prototype harvesting node, itself called 'Heliomote', suggested ways to model energy harvesting and consumption numerically, and resulted in the design of a scheme to achieve indefinite operations.

Recently, Noh et al. have studied QoS-aware routing (Noh et al., 2007) and low-latency routing (Noh et al., 2008) in solar-powered WSNs. In their WSN, transmission ranges are periodically determined, based on an estimated energy harvest and a predicted energy consumption. Then, the routing program running at each node selects one of the neighbors of that node which is likely to provide a desirable transmission performance, including low latency and high reliability. However, this approach is based on the predictions of variables such as the hop-count to the sink, the energy harvest and the rate of energy consumption, which are inevitably inaccurate, and thus its performance is not always satisfactory.