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Energetic sustainability of routing algorithms for energy-harvesting wireless sensor networks

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Abstract

A new class of wireless sensor networks that harvest power from the environment is emerging because of its intrinsic capability of providing unbounded lifetime. While a lot of research has been focused on energy-aware routing schemes tailored to battery-operated networks, the problem of optimal routing for *energy harvesting wireless sensor networks* (EH-WSNs) has never been explored. The objective of routing optimization in this context is not extending network lifetime, but maximizing the workload that can be autonomously sustained by the network.

In this work we present a methodology for assessing the energy efficiency of routing algorithms for networks whose nodes drain power from the environment. We first introduce the *energetic sustainability* problem, then we define the *maximum energetically sustainable workload* (MESW) as the objective function to be used to drive the optimization of routing algorithms for EH-WSNs.

We propose a methodology that makes use of graph algorithms and network simulations for evaluating the MESW starting from a network topology, a routing algorithm and a distribution of the environmental power available at each node. We present a tool flow implementing the proposed methodology and we show comparative results achieved on several routing algorithms.

Experimental results highlight that routing strategies that do not take into account environmental power do not provide optimal results in terms of workload sustainability. Using optimal routing algorithms may lead to sizeable enhancements of the maximum sustainable workload. Moreover, optimality strongly depends on environmental power configurations. Since environmental power sources change over time, our results prompt for a new class of routing algorithms for EH-WSNs that are able to dynamically adapt to time-varying environmental conditions.

Keywords: Wireless sensor networks; Energy harvesting; Routing algorithms

1. Introduction

Research efforts in the field of communication in *wireless sensor networks* has led to the development of several energy aware routing protocols [1] which aim at choosing the routes for transferring data from sensors to base stations so that network lifetime is maximized [12]. When sensor nodes are battery-powered, network lifetime is a suitable metric for steering the design of optimal routing algorithms. In fact, battery replacement is a critical issue for most of the applications for which WSNs are deployed, so that the lifetime should be ideally unlimited.

In order to overcome battery limitations, a new generation of sensor nodes have been developed that harvest power form the environment by means of *energy scavengers* [8–10,15,21]. For instance, solar panels are very well suited to power nodes which are scattered on a wide region for environmental monitoring purposes. We call *energy-harvesting wireless sensor network* (EH-WSN) any network composed of environmentally powered nodes.

In EH-WSNs, if the average power spent by each node to accomplish its task for a given workload is lower than

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the power it can harvest from the environment, then we say that the workload is *energetically sustainable*. In general, a node can perform three kinds of activities: sampling, processing, relaying packets. Routing protocols mainly affect packet relaying, but in some cases they also affect data sampling and processing. For instance, if the same target phenomenon can be observed by many sensors scattered in the same region, the routing algorithm can dynamically choose among them according to some optimization criteria.

Since routing affects the workload imposed to the nodes, data delivery protocols for EH-WSNs must be aimed at generating an energetically sustainable workload. Thus, instead of maximizing lifetime [6,9,12], the problem becomes maximizing the workload under given environmental power constraints. We call this problem *energetic sustainability*. In general, routing algorithms developed for battery-operated WSNs do not provide optimal solutions to this problem. For instance, battery lifetime is usually maximized by using the minimum amount of power at each node and by differentiating the routes in order to make workload distribution as uniform as possible [18]. On the contrary, energetic sustainability is granted by relaying packets on the routes that can maximally exploit environmental power, taking into account the amount of power available at each node. In practice, while battery-operated WSNs are subject to energy constraints, EH-WSNs are subject to power constraints.

Recently, some researchers have proposed routing protocols for sensor networks having both battery-powered and solar-powered nodes [22,23]. They have shown that network lifetime can be significantly improved by *solar-aware routing* algorithms using solar-powered nodes to release constraints on the power budget of battery-operated ones. The proposed algorithms assume that solar powered nodes have unlimited power and can sustain an unlimited workload. Hence, they do not address energetic sustainability issues.

In this work we propose a new methodology for assessing the energetic sustainability of routing algorithms. First, we define the *maximum energetically sustainable workload* (MESW) for a given EH-WSN (*Net*) with a given routing algorithm (*rAlg*) under given environmental power constraints (*Pmap*), denoted by *MESW*(*Net*,*rAlg*,*Pmap*). Second, we define the optimum MESW for a given sensor network with a given power map, denoted by $MESW^{opt}$(*Net*,*Pamp*), as the best MESW achievable by any routing algorithm applied to the network:

$$MESW^{opt}(Net, Pmap) = \max_{rAlg}\{MESW(Net, rAlg, Pmap)\} \quad (1)$$

The optimality of a routing algorithm can then be expressed by the ratio between *MESW* and $MESW^{opt}$, that takes values in the [0,1] interval.

Exact algorithms for computing $MESW^{opt}$ in polynomial time have been recently developed [3], while simulation-based techniques for evaluating the *MESW* of a given routing algorithm represent the main contribution of this work.

The rest of the paper is organized as follows: In Section 2 we present the EH-WSN model, with particular emphasis of power consumption and workload representations. In Section 3 we state the problem of energetic sustainability and we present a new methodology to evaluate the MESW of a given routing algorithm. In Section 4 we outline the implementation of the proposed methodology on top of an open source network simulator [13]. In Section 5 we report experimental results and we discuss the energetic sustainability of many different routing algorithms applied to the same EH-WSN; in Section 6 we draw conclusions.

2. EH-WSN model

We consider multi-hop wireless sensor networks composed of *sensors*, *routers* and one or more *base stations*. Sensors and routers have wireless connectivity and harvest power from the environment, while base stations are sink nodes with unlimited power supply and network connectivity. Data are sampled by sensors and routed to a base station. Sensors can also act as routers for other nodes.

2.1. Power model

To study the energetic sustainability of a workload for a given routing algorithm we need to model *packet energy*, that is the energy spent by each node to process a packet, and *available power*, that is the environmental power available at each node to sustain packet processing.

Packet energy includes the energy needed to produce (or receive) the packet, to process it and to relay it on the selected route. Production (or reception) and processing energy can be regarded as constant contributions [5], while transmission energy depends on the distance between the transmitter and the receiver. For instance, the transmission power level of a node can be dynamically adjusted to the minimum level needed to provide the required signal to noise ratio at the target receiver, chosen within a given transmission range. Since the power loss of a radio channel grows quadratically with the distance (d) between transmitter and receiver [2], a quadratic model of packet energy ($pE = pE0 + pE1 \cdot d^2$) can be used to capture both the constant contribution of packet processing and the distance-dependence of transmission energy. Investigating more realistic transmission power models is beyond the scope of this work. Nevertheless, the proposed methodology can be applied to any power model and possibly used to explore the effects of the power models on the sustainable workload.

Packet energy is not the only contribution to the power budget of a WSN. In fact, sensor nodes and routers spend a sizeable amount of idle power waiting for incoming events or listening for incoming packets [12,16]. Dynamic power management techniques and energy-aware communication