Harvesting Aware System for Sustainable Mobile Sensor Networks

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Abstract

One of key challenges in deploying large-scale Wireless Sensor Network (WSN) is system longevity. In this paper we propose an harvesting aware system of SMSN (Sustainable Mobile Sensor Network) as a way to extend system lifetime. The mobile sensor nodes visit remote energy station to recharge battery when node's energy drains below a threshold level. Our framework consists of energy model, motion control system and data transfer protocol. The simulation result shows the sustainability of our SMSN. Our results along with simulation can be used for certain guideline for realistic development of such systems.

Keywords: *Energy Harvesting, Sustainable Mobile Sensor Network, NS2 Simulation*

1. Introduction

Wireless sensor networks (WSNs) consist of resource constrained nodes which communicate with each other over wireless channel [1]. In these types of networks, energy is one of most critical resources because the nodes are usually battery-powered and have not enough lifetimes for most applications. Moreover, it is impractical to replace their batteries without human intervention owing to its high operational cost.

There are a few approaches proposed to extend lifetime of WSNs. One of those approaches is to use mobility in order to save energy in transferring data over multiple hops [2, 3]. The mobile base station or data collector moving over the sensor field can collect data from the static sensor nodes over single hop radio link. While this approach can make the network to last longer, the latency of data transfer may be increased. On the other hand, several technologies to extract environmental energy have been demonstrated from solar, motion-based, biochemical, vibration energy sources [4, 5]. But, there exist still highly variable conditions in terms of availability of environmental energy, e.g., solar cell in night or fluorescent light in an indoor area.

A new key to solve that kind of situations is to use *energy station* that provides energy inherent from the environment. We consider it as an energy "reservoir" or "well" that store environmental energy or batteries. The example of such devices includes fluorescent light in indoor area or vibrational pump that can be installed manually. We assume such energy station cannot move. Rather, the sensor node must be mobile and controllable, and differ from stationary sensor networks where the sensor nodes do not move once deployed. Fortunately, with the advance of energy efficient robot technology, it is shown that a cheap, light robot can be used to recharge the other sensor nodes as well as itself [6]. If such mobile node knows where a nearby energy station is, it could move or fly to there in order to replenish energy for itself and then return to its original service area (see Figure 1). This new technology of self energy replenishment is not mature yet, and has not been addressed in detail.

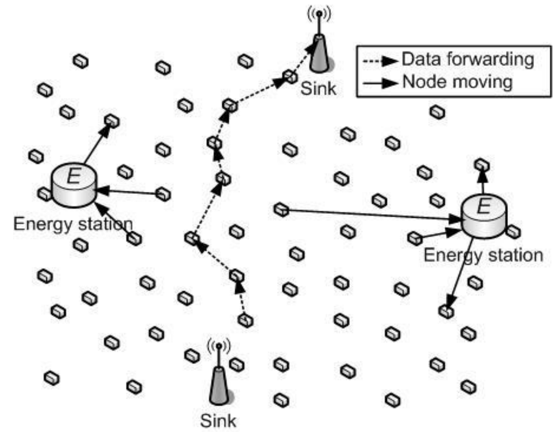

Figure 1. Mobile Sensor Network Architecture with Remote Energy Stations

In this paper, we propose a novel framework of Sustainable Mobile Sensor Network (SMSN) as a solution to extend system lifetime. The proposed framework consists of energy-harvesting mobile nodes and sparsely deployed energy stations. First we describe the system model, the basic assumptions, and the energy consumption and harvesting model. The system architecture provides network sustainability for a dense mobile sensor network by exploiting energy supply stations and mobile nodes moving in the environment. After then, we propose a new data transfer protocol, which consists of message advertisement protocol and harvesting aware routing protocol. There were some works addressing the problem of energy-aware and geographical routing with distributed energy replenishment for multi hop wireless sensor networks [7]. However, these works do not consider any deficient situation like when the environmental energy cannot be supplied due to bad weather such as rain or night. On the other hand, our harvesting aware routing protocol makes decision by jointly considering neighbor nodes' various information like location, residual energy, link connectivity, and so on.

The rest of the paper is organized as follows. In Section 2 we explain our harvesting aware framework and present a harvesting aware data transfer protocol in Section 3. We present our simulation results in Section 4. Finally, Section 5 concludes the paper.

2. The Sustainable Mobile Sensor Network (SMSN)

We consider the wireless sensor network densely deployed with sensor nodes. The system has two main components, base station and sensor node. First one is static base station which collects data from sensor nodes as a *sink node* or supply energy to sensor nodes as a *energy station*. For communication, this station can send packet with its interested query or its own location to neighbor nodes periodically. Second one is mobile sensor node which communicate with another node and move by itself. The node hardware consists of processing, network, mobility, and rechargeable power units.

We assume that each node knows its own properties like the position, the remaining energy, the battery capacity, and so on. In addition, neighbor nodes exchange the information through broadcasting the periodic advertisement messages.

2.1. Energy Consumption and Harvesting Model

In this paper, the energy consumption model of the mobile node considers radio states and moving phase. The radio states include at least transmit, receive, sleep and off. The moving phase means that the node is under moving for energy harvesting at the state of radio off. Thus, the total energy consumption of a node can be modeled as adding up the factors according to radio states or moving phases.

If the power consumption in moving a unit distance is proportional to the speed of movement, the total energy consumption of the node is computed as follows.

$$E_{node} = n_t E_t(b) + n_r E_r(b) + t_{sleep} E_{sleep} + dE_{mov}(v) \quad (1)$$

where n_t is the bit number of packet transmission, $E_t(b)$ is the transmission energy per bit, n_r is the bit number of packet receiving, $E_r(b)$ is the receiving energy per bit, t_{sleep} is the sleep time, E_{sleep} is the sleep energy, d is the trip distance, and $E_{mov}(v)$ is the motion energy as to speed.

We assume that the node can harvest energy only when it nearly approximates a neighbor energy station. For example, the battery capacity E_b denotes such a capacity limit for each node in the next figure.

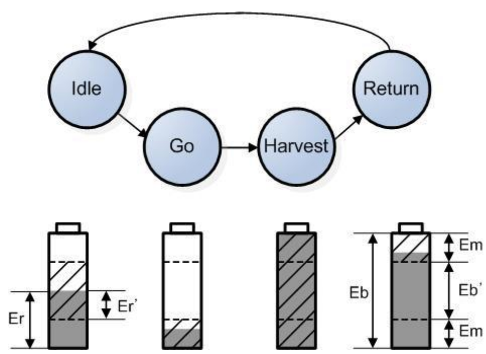

Figure 2. Motion States and Battery States for Motion Control System

2.2. Motion Control System

The objective of motion control is to decide the time to recharge node in order to maintain node energy level above a threshold. The motion control process consists of two phase: idle phase and moving phases. At the idle phase, the process periodically checks two conditions, while the node services its normal sensing and data gathering operation. The first condition indicates whether the node can make round trip to a nearby energy station. It is formulated as the following equation.

$$E_b'(i) = E_b(i) - 2E_{mov}(v_i)d(i, S_i) > 0 \quad (2)$$

where E_b' is effective energy capacity which is an amount of total battery capacity minus moving energy consumed for a round trip to the energy station. It indicates maximum effective energy that can be consumed during the idle phase.

The second one is to check to determine when the node starts to move to the energy station before the energy depletion. This condition is formulated as follows.

$$E_r'(i) = E_r(i) - E_{mov}(v_i)d(i, S_i) > 0 \tag{3}$$

where $E_r^{'}$ is defined as effective residual energy. It means actual remaining energy that practically will be available to consume for the idle phase.

3. Harvesting Aware Data Transfer Protocol

Our network protocol consists of two phases. The first phase is about occasionally advertising some specific information of a node to its neighbors, and the second one is energy-efficient multihop routing protocol to forward data packets.

3.1. Node advertisement protocol

During this phase, sensor node tries to maintain its own information as well as one-hop neighbors' information such as location, residual energy, average radio-on and radio-off time. Moreover, each node must know the location of nearest energy station in order to replenish its own energy. Thus when the sensor node triggers a timer periodically, or the node starts or finishes to move, one advertisement packet whose content includes E_b', E_r' as well as its location is sent to one-hop neighbors for routing protocol. Besides, the sink node broadcasts the packet with location information of itself to his one-hop neighbors for the purpose of gathering data.

On the contrary, the message advertisement is more complex in case of the energy station. The energy station needs to deliver its location information to farther nodes for energy harvesting. This packet could be flooded from one station to neighbor nodes *within* reachable range determined from the communication hop. However, there exists still distance gap between actual reachable range and maximally reachable range, making some blind nodes, as in Figure 3. To reduce this deficiency, we propose an active communication mode. In this mode, such blind node occasionally sends the "Energy Query" packet to their neighbors in order to get the location information of near located energy station. Then, any non-blind neighbor that receives the packet might reply to the querying node with "Energy Update" packet. Therefore, the active mode covers broader propagation area than default flooding mode.

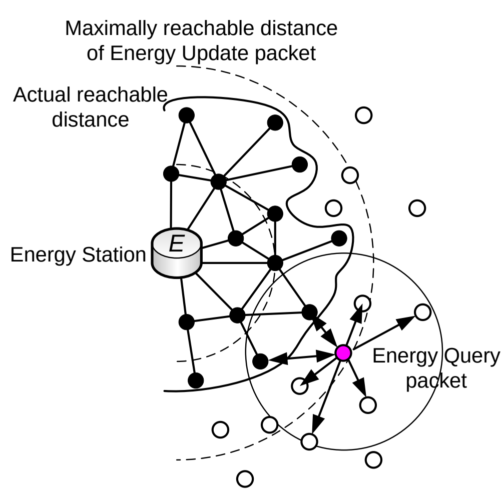

Figure 3. Concept of the Active Mode with "Energy Query" Packet

3.2. Energy-aware Geographic Routing Protocol

We assume that the node i is forwarding progressively a data packet, whose destination is R. Each node locally maintains its own information as well as one-hop neighbors' information such as location, residual energy, average radio-on and radio-off time. Moreover, each node must know the location of nearest energy station through periodically advertized messages from near located energy stations. Node i forwards the packet to the neighbor that minimizes the cost $C_L(N_i, R)$ as follows:

$$C_L(N_i, R) = \frac{1}{\alpha \cdot D_N(N_i, R) + (1-\alpha) \cdot E_N(N_i)} \quad (4)$$

where $0 < \alpha < 1$ is an weight factor, $D_N(N_i, R)$ is the normalized progressive distance from i to a neighbor N_i towards R and E_N is the normalized effective consumed energy on node N_i. $D_N(N_i, R)$ and $E_N(N_i)$ are computed as follows:

$$D_N(N_i, R) = \frac{D(N_i, R)}{\max\{D(N_i, R)\}} \quad E_N(N_i) = \frac{E(N_i)}{\max\{E(N_i)\}}, \quad (5)$$

where $D(N_i, R) = [d(i, R) - d(N_i, R)] \cdot \tau_i \cdot \tau_{Ni}$ and $E(N_i) = \beta E_b{}'(N_i) + E_r{}'(N_i)$. The distance $d(i, j)$ represents the Euclidean distance between node i and node j.

The intuition for minimizing the estimated cost function is as follows. Minimizing the cost in Equation (4) means maximizing the denominator. The denominator is a linear combination of both geographic and energy related terms. The first part is $D_N(N_i, R)$ which represents how much progress one packet can make toward the destination. The physical meaning of maximizing Equation (5) is to maximize the efficiency of packet transmission and decrease the energy consumed per packet, as each transmission failure increases a node's energy consumption due to retransmission. The estimated energy availability $E_N(N_i)$ is represented by linear combination of energy harvesting efficiency and effective residual energy on the battery. Therefore, Equation (4) balances elements of advancement per transmission, energy harvesting and residual energy.

4. Simulation Results

We implemented the energy harvesting model, motion control algorithm and harvesting aware data transfer protocol using by NS-2 software [8]. For energy harvesting and mobile energy consumption of a node, the existing mobile node model and energy model were extended. The mobile node model takes charge of moving the node. The harvesting energy model performs the task of consuming or replenishing energy as to packet transmission, idle, movement, and energy harvesting. The core program is responsible for transferring packets and self-controlling its own motion.

The simulated sensor network has $2000 \times 2000\ m^2$ square region with 2000 mobile sensor nodes, which deploy randomly and have identical battery capacity, transmission/idle power, moving speed. The maximum transmission range was set as 250 m. We use 4 sink nodes which are deployed at the fixed locations. The stationary energy stations including sink were deployed uniformly at the equidistant grid locations, whose cell size is set to 500 m. Thus, total number of energy stations is 25 on the whole sensor field. For communication traffic, one packet per every 1 second was sent from randomly selected 10 source nodes to sinks nodes.

Figure 4 shows the average residual energy distribution for 400 sensor nodes during 1000 seconds. It is clear that in the stationary sensor network the number of dead nodes increases as time goes. Therefore, the poor performance of the network is due to sensor nodes with run-out batteries. In the SMSNs, nodes can move to a energy station and recharge energy as they need. The simulation result shows that the SMSN is sustainable. Next we compare two cases of the SMSNs with and without using "Energy Query" packet. It can be seen that the active mode has less dead nodes than the default flooding mode. Of course, blind nodes that have not sufficient energy to move to the station would eventually be dead due to energy depletion.

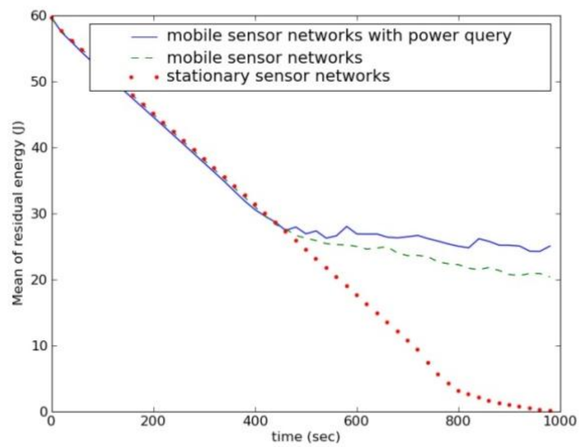

Figure 4. Average Residual Energy for 400 Nodes

5. Conclusions

In this paper we addressed the possibility of energy harvesting in sensor networks deployed with energy stations. The main idea is to make mobile node to make round trip to remote energy station in order to harvest energy without depletion, thus enabling to sustain the network forever. We designed a harvesting aware system that can control the motion of the mobile nodes according to the energy consumption behavior. Our future works include applying our results to the realistic environment.

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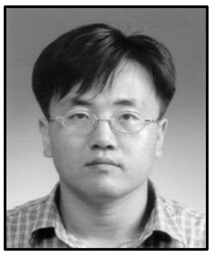

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