

# Energy-Aware Routing in Wireless Sensor Networks with Adaptive Energy-Slope Control

Hanh-Phuc Le, Mervin John, Kris Pister, *Member, IEEE*  
University of California, Berkeley

**Abstract**— Wireless sensor networks (WSNs) have proven and increased their popularity in many different applications where sensitive information is collected at sensor nodes and forwarded to a central analysis (CA) center. However, the constraints of limited resources and requirements for environment-dependent connectivity and life cycle have urged designers to seek more efficient WSN infrastructures. In this project, we plan to explore the major constraints (i.e. network survivability, energy reserves, power scavenging), metrics, and tradeoffs affecting energy-aware routing strategies. The proposed routing strategy utilizes an adaptive energy-slope control (AESC) method to keep each and every node alive for a certain required maintenance/life-time period. In the proposed strategy, the network is expected to cope with worst cases of environment-dependent connectivity while still sustain energy-efficient connections in normal situations. Simulations will be conducted to assess the performance of the AESC routing method.

**Index Terms**—energy efficient, routing, wireless sensor networks

## I. INTRODUCTION

Unlike in personal electronics like laptops or cell-phones where the CPU and display are usually the overwhelming power hungry components [1], communication in a wireless sensor mote takes up most of the power consumption of the mote even if though it runs at a much lower data rate. At the same time, the majority of motes in a wireless sensor network (WSN) are powered by battery, which is energy limited, or by recently developed energy scavengers like that reported in [10], which are power limited. Only one or a handful of motes, usually the access point (AP) of the network or sub-network, are AC line-powered. Furthermore, while the battery life of rechargeable personal electronics is expected to be within a few days, that of a wireless sensor mote can be months or even years in some situations. Ideally, these batteries along with other components should be small enough to fit in to a wireless sensor mote smaller than one cubic centimeter [14]. The inherent tradeoffs between storage

energy, cost, and size are challenges to the design of wireless sensor networks while still maintaining their functionalities and connectivity.

To date, an increasing number of efforts have been made to deal with the challenge as WSNs become a highly sought after option in a wide range of application, including industrial production lines, solar power systems, building automation, medical devices, weather monitoring and many others. At the network layer, issues in routing, addressing and support for different classes of services have proven to considerable.

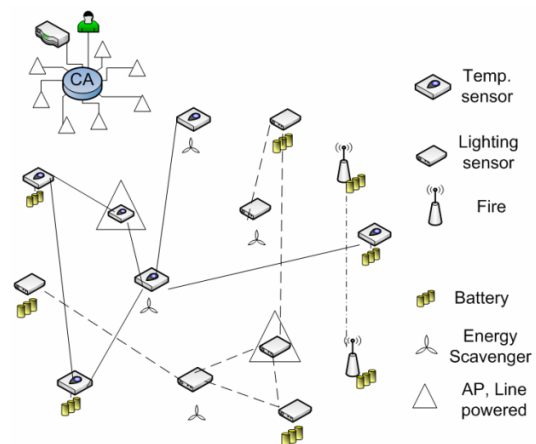


Fig. 1. Wireless sensor network with multiple sub-networks and power supplies.

In this paper, we will address the routing problem, discuss current solutions, and propose an energy-aware routing protocol that potentially improves network routing performance and thus, its connectivity/survivability. Although there are a number of metrics for routing protocol performance, we believe a useful and critical one is network survivability. The traditional “SmartDust” view of wireless sensor networks had non-critical nodes die (e.g. battery dead, connectivity lost) with no apparent performance hits to the application. However, in a realistic deployed wireless sensor network, the first mote to “die” will often trigger an expensive and unwanted truck roll. The network survivability metric [6] ensures that connectivity is maintained as long as possible and that those individual motes do not die before their expected lifecycle. The lifecycle could either be set by the expected life of the battery or some application, the next scheduled maintenance visit (i.e. to replace the batteries).

## Target Application

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Hanh-Phuc Le is with University of California, Berkeley (e-mail: phucle@eecs.berkeley.edu).

Mervin John is with University of California, Berkeley (e-mail: mervin@eecs.berkeley.edu).

Kris Pister is with University of California, Berkeley (e-mail: pister@eecs.berkeley.edu).

Home/building automation is chosen as the target application to apply the proposed routing strategy. However, it can be applied to any WSNs that have considerations for energy-aware activities. In home/building automation, there are a variety of sensor types, including HVAC, fire, lighting and temperature. Each of which set up different sub-networks that geographically overlap each other as illustrated in Fig. 1. It is important that network connectivity/survivability is maintained during a certain lifecycle. The authors of this paper agree that if different sub-networks geographically overlapped can talk and contribute intermediate routing nodes to each other, the connectivity and survivability of the sub-networks can be significantly improved. While the number of sensing elements within each sub-network remains unchanged, the network's communication density and network connectivity increases almost exponentially to the number of network participants as illustrated in Fig. 2. As the result, an energy-aware routing scheme has more energy-cost-effective paths to choose from to optimize the total energy consumption and survivability of the whole network.

In addition, as suggested in Home/Building Automation Routing Requirements in Low Power and Lossy Networks, IETF [12, 13], efficient energy-aware routing should take into account the different power sources types in order to maintain network connectivity. Beside battery and line power supply, energy scavenger have been studied and developed to improve a node lifetime and thus, the network survivability. In addition to the link distance/power, an energy cost associated with the current battery reserves as well power type should be considered.

The rest of the paper is structured as follows. Section II reviews some of the routing protocols for WSNs. Section III introduces our energy-aware routing scheme. Preliminary simulations are presented in Section IV. Section V concludes the paper.

## II. ROUTING TECHNIQUES FOR WSNs

There has been considerable research in the area of energy efficient routing protocols. The research literature can be divided into two categories: *proactive* protocols, such as Destination-Sequenced Distance Vector (DSDV), Cluster-Head Gateway Switch Routing (CGSR) and Wireless Routing Protocol (WRP), which keep and update information in routing tables, and *reactive* or on-demand protocols, such like Ad hoc On Demand Distance Vector (AODV) and Dynamic Routing System (DRS), which construct routing tables when a packet is being sent to the destination.

In reality, the nature of an environment where WSNs are located is unreliable, dynamic, and indeterminate. That requires more efforts to put into routing strategy to make wireless ad-hoc network protocols feasible in WSNs, especially with energy limitation. The energy efficient routing in WSNs using probabilistic strategies proposed in [2] utilizes a random flooding (RF) strategy with the major assumption of knowing the position of every node in the network. This approach has a major drawback of still relying on flooding techniques which are well-known to be energy-inefficient solutions, especially in dense networks. To avoid the overhead

due to flooding, the work in [3] proposed a gradient routing technique. Although this technique can reduce the total power

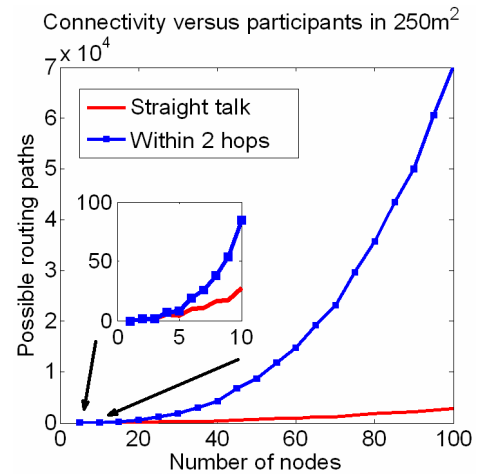


Fig. 2. Connectivity increase exponentially with the number of nodes in a wireless sensor network.

consumption in the network it cannot ensure the survivability of the network. As the routing metric used is only dependent on the number of hops to calculate the energy cost and make routing decision, the network can be disconnected if a node becomes a favorite intermediate node for many routing paths thus suffers from heavy traffic and dies down quickly. [4] takes a step further into energy aware routing by considering signal strength and residual energy of a node for routing decision. This routing strategy potentially saves some energy by turning off unused nodes and utilizing the ones with more energy left but is not necessarily energy-efficient and optimal for the network as a whole, due to the fact that with the same receive power  $P_r$ , the transmit power  $P_t$  is proportional to  $R^2$  ( $R$  is the distance). Therefore, it is not immediately clear that routes with less hops but with more power consumption (signal strength) at each hop is better than routes with more hops but with less power consumption at each one. Research is being done based on the knowledge of network geography from GPS as reported in [5]. However, GPS positioning and update rate may not be available or favorable in many internal applications. The network survivability is carefully addressed in [6] with a probabilistic routing strategy with AODV and a set of "good paths" in an effort to deplete the nodes in the network equally and make a more graceful degradation of the network. However, this approach could be improved by putting nodes not used in the current routing table to sleep mode. In addition, equal node depletion may not be possible nor an optimal solution in networks with different mote sub-networks, where each mote type may have different power consumptions, energy type, expected lifecycle, and power types (i.e. AC, scavenging, battery).

With the understanding of conventional approaches' pros and cons, we propose a new routing method that can be applied to a more practical situation in home/building automation applications where there are several types of motes with different maintenance schedules. An adaptive energy-slope control routing (AESC) strategy and protocols will be introduced in Section III to assure network connectivity during

expected lifecycle for maintenance while still achieving energy efficient routing. The proposed protocol optimizes the use of scattered AC and energy scavenging motes in the network.

### III. ADAPTIVE ENERGY SLOPE ROUTING

The power sources in WSNs [13] can be divided into three categories, energy-limited (battery-powered), power-limited (energy scavengers), and unlimited sources (AC powered). Each category has a specific optimization strategy based on their energy constraints. A battery-powered node is energy-limited in that starts with a fixed amount of energy and requires maintenance once it is depleted. If we assume a maintenance schedule for each type of mote (a single sub-network), then it is implied that the sub-network will remain connected until the maintenance period (within some safety margin). A power-limited scavenger is also battery powered but also has the advantage of replenishing its reserves with scavenged energy. The routing protocol should ensure that the mote optimizes the power coming into the mote, especially if the mote is near its maximum energy capacity. An unlimited source has zero energy cost when used for routing and should be used accordingly.

Fig. 3 shows the concept of routing with adaptive energy slope control protocol. For one certain type of motes, all batteries start with initial charge  $Q_{init}$  and depleted at  $Q_{dep}$  where the sensor and its circuit stop functioning. During this range of charge, because their voltage remains relatively constant, charge can represent energy in our analysis and algorithm. The ideal energy/lifecycle slope  $s_0$  for one sub-network derived from the total initial charge of a node  $Q_{init}$  and an expected time to maintenance  $t_m$ :

$$s_0 = \frac{Q_{init}}{t_m}$$

In this protocol, the ideal battery discharge line acts as a threshold for average power consumption over time to make sure the node stays alive until the maintenance time  $t_m$ . In a scenario when the traffic increases at this node, its discharge rate will be steep. As soon as the charge drops lower than the threshold line, the energy metric used for routing will proportionally increase the cost of using the route. As the routing table is reconfigured and with less or no routing (the node goes to sleep mode) through it, its communication power consumption will be reduced and the discharge slope will be less steep. Over time, it comes back to above the threshold line and it can take the role of intermediate node within the routing path again. If the mote's energy reserve is assisted by an energy scavenger it will charged to above the threshold slope. Different types of subnet have different types of motes, different maintenance schedule, and thus different energy slope.

With the scavenger-assisted battery, the slope is less steep in an equivalent event because the scavenger continuously provides charge to the battery.

With the scavenger with a small battery or just a capacitor as the storage, the input and output power should be balanced or the scavenged energy will either be wasted at low traffic or exhausted with too high traffic for a long time. Fig. depicts the situation that the scavenger is initialized with  $Q_{sc}$ . During its lifetime, with low traffic,  $Q_{sc}$  is at  $Q_{sc,max}$ , while in busy time, the control algorithm assures that its  $Q$  not drop below a certain level to keep the average  $Q_{sc}$  constant – balanced input and output power, and to keep the circuit associated with it still function correctly.

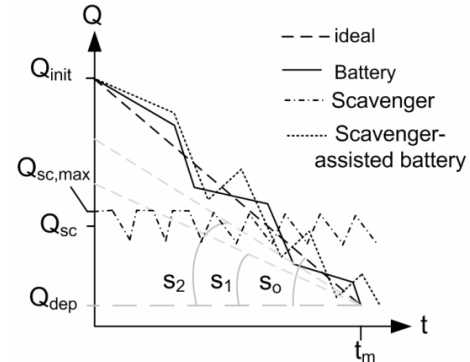


Fig. 3. Adaptive energy slopes for various energy sources

This method suppresses a mote from being a favorite intermediary node with high traffic for long period of time, which results in the node being depleted and disconnected from network, potentially affecting connectivity within the entire network. When there are more than 1 possible routing paths, the lowest energy-cost route will be chosen by the routing algorithm to minimize the overall energy consumption of the network. However, as energy reserves are depleted, updated routing tables ensure that different paths are chosen over time.

#### Adaptive Energy Metric

In this paper, the adaptive energy slope is incorporated into the energy matrix as cost for routing. The cost for each link between 2 nodes is calculated from the distance  $D_{ij}$  between them and the energy slope  $s_0$  over lifecycle. If there is a scavenger, the input power  $P_{in}$  from the scavenger is also considered.

$$C_{ij} = D_{ij} + \alpha \frac{1}{s_0} \left( +\beta \frac{1}{P_{in}} \right)$$

The weighing parameters  $\alpha$  and  $\beta$  must be chosen carefully to ensure the protocol performance.

#### Update Rate

Since the topology and energy reserves of the sensor network frequently change, the routing tables should be build adaptively. The exchange of routing information should not add a significant overhead to the network but must be conducted at a rate that ensures network connectivity and

survivability.

#### IV. SIMULATION AND RESULTS

##### A. Wireless Sensor Network Simulation Tool: Prowler

After examining a number of WSN simulators, we carried out our simulations using a modified version of Prowler, a probabilistic events-driven simulator. Although it targets the

complete evaluation of the protocol should include a realistic implementation of the MAC layer. The radio propagation model determines the strength of the transmitted signal at a point to all other receivers in the system. The strength of the signal along with the sensitivity level of the receiver determines the signal reception conditions for each packet. We used the Pister-Hack model, as shown in the equation below, where the signal strength from the transmitter  $P_t$  to the

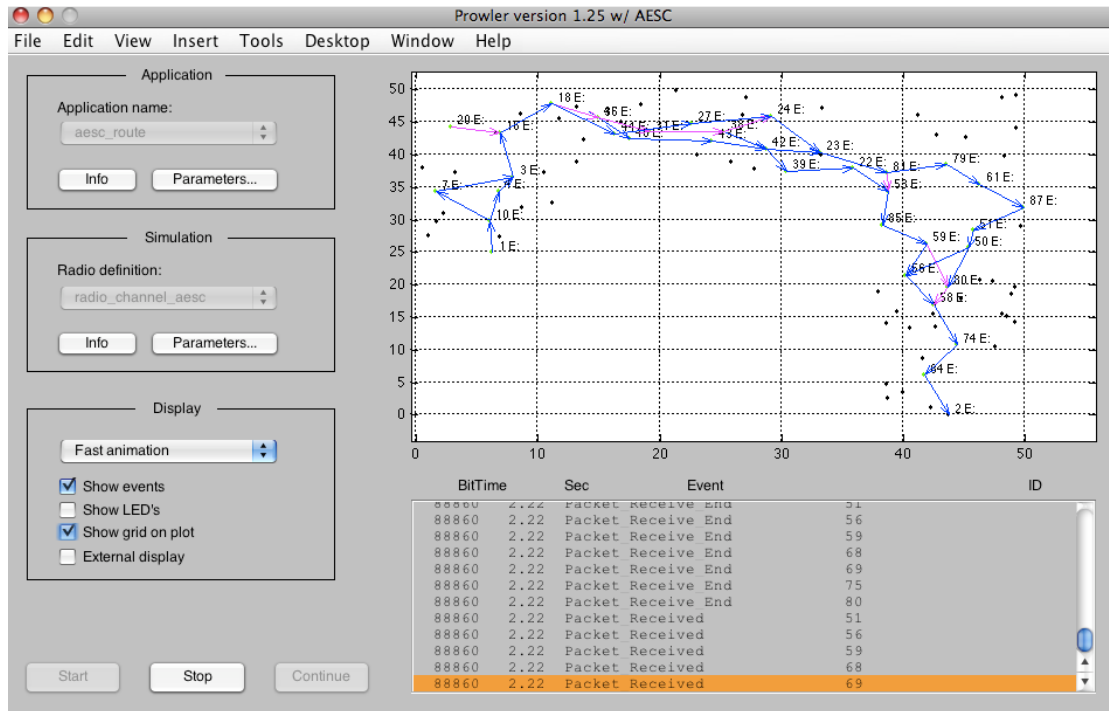


Fig. 4. Modified Prowler simulation tool while simulating energy aware routing along multiple paths.

MicaZ platform running TinyOS, it can be used regardless of the hardware platform or operating system running on the motes [11]. One of the main advantages of the Prowler framework is its ease of use, due to the popular Matlab environment on which it runs. It provides a customizable GUI for entering network parameters (topology type, number of motes) and animation. Prowler consists of three modules. The main module, or engine is called prowler and implements an events queue, similar to the TinyOS framework, to handle events called by the user (e.g. Set\_clock, send\_packet) or are fired by other events (e.g. packet\_received, clock\_tick, timer\_fired). The application module/layer provides access to user generated events. The radio module handles both the MAC-layer model and the radio propagation model.

##### MAC-layer and Radio Propagation Model

For our simulation, the MAC layer was partially abstracted away by providing for direct transfer of packets from the transport layer of one mote to the transport layer of its neighbor. Thus, we can evaluate the benefits our routing protocol independently of the MAC layer. However, a

receiver  $P_r$  is evaluated from a deterministic propagation function (modeling the decay of signal strength with distance  $D$ ) and a by a random distribution (modeling the fading effect, physical obstruction, time-varying interference).

$$P_r = P_t \frac{1}{1 + D^\alpha} + \text{rand}[0..-40] \text{dBm}$$

##### B. Power Aware Routing Simulation

Each sub-network was assigned a specific maintenance schedule. For example the next scheduled visit for the HVAC sub-network may be six months away while for the lighting network, it may be 2 years away. The majority of the motes were battery powered with identical amounts of initial energy within each sub-network. A few energy-scavenging motes were assigned an average power input rate and scattered across the sub-networks. A couple of AC powered AP were passed at centralized positions in the network topology. The Prowler simulation framework was modified to add an energy layer that tracks the energy consumption/production of each mote over the course of the simulation. Transmission uses

20nJ/packet while reception uses 30nJ/packet but the actual costs can be varied based on the platform and radio used. The module triggers a stop simulation event when the first mote dies (network survivability is the key metric here).

The energy metric and energy consumption model are the critical components of our routing strategy. The energy metric used to evaluate a specific path incorporates the cost of using the path, the energy health of the nodes along the path, the lifecycle of the nodes, topology of the network, and power

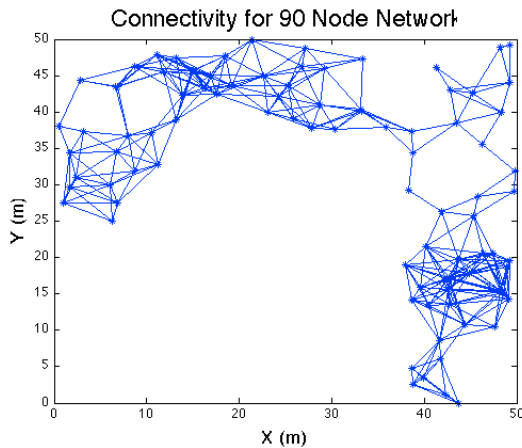


Fig. 5. Connectivity graph of nodes in the network. Layout is a three-room corner office/home setup over a 50mx50m area.

type (i.e. scavenging, battery, AC).

For our initial simulations, we used a globally generated routing table. We assumed that the master AP had knowledge of the link costs and energy reserves of every mote in the network. Using the routing cost metric previously given, the optimal route at a given time was calculated using a Floyd–Warshall algorithm to compute the shortest paths along a

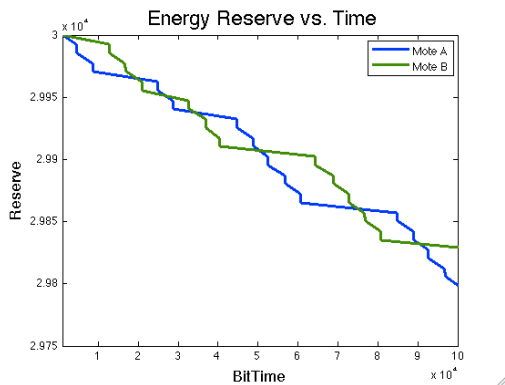


Fig. 6. Mote A and B are intermediary nodes in two separate but good routing paths. As the routing table is updated intermittently, communication switches between the two paths. For both motes, the optimal energy/lifecycle is maintained over time.

weighted graph. Future simulations will use WSN oriented routing algorithms like AODV combined with our power aware routing scheme.

The network topology consisted of 90 nodes in typical office setup as shown in Fig. Among the nodes, 30 were part

of the lighting sub-network, 30 were part of the HVAC sub-network, and 30 were part of the temperature sub-network.

A few nodes in the network act as information sources while others were configured as information sinks. Each source injected a packet to the network on average once a

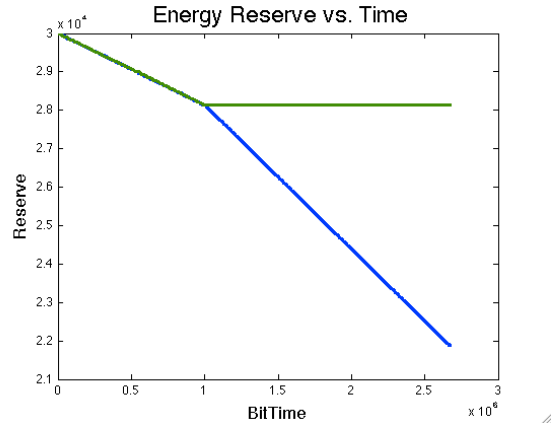


Fig. 7. The AESC routing protocol has been turned off at  $1e5$  bit time. The intermediate node along the energy-efficient, or "favorite", path starts dying out faster.

second. The routing table was updated periodically about once every 10 secs.

Fig. 6 shows the energy reserves of two motes in the network. Mote A simulates a node in the most energy efficient path (the favorite path) in terms of the energy costs along the route. Mote B simulates a node that is along one of the sub-optimal paths. However, in our routing scheme both paths form a set of good paths to be used by the routing layer. In this example, the packets used the primary path about half the time but in order to meet the expected lifecycle; a communication will use the other sub-optimal paths at different times. In this manner, the overall energy consumption of the network is reasonably minimized without burning the energy of any single nodes along the optimal paths. Fig. 7 shows an intermediate node dying off faster once the AESC routing scheme is turned off and only the most energy-efficient path is used.

#### Practical Considerations for Future Simulations

For a realistic simulation, a number of other issues must be addressed. An accurate model for the MAC layer should be incorporated into the radio module. Other network parameters that should be considered include latency, throughput, and uptime. The effect of the routing update rate on network performance should be analyzed. Most importantly, the energy and consumption metrics used for the routing algorithm should be adjusted based on application specific and or even site-specific data. Other security considerations include the validity of shared information (e.g. lighting sensors lie to HVAC sensors about their energy reserves in order to maximize their own lifetimes), encrypting data transmitted through other sub-networks.

## V. CONCLUSION

In this paper, we present a energy-aware routing strategy for WSNs. Our approaches optimizes the use of various energy types within a network based a on maintenance schedule for each sub-network. Initial simulations using a modified version of the Prowler network simulation tool were conducted. A comparison between the proposed routing strategy and existing strategies will be conducted.

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