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Online energy aware routing in wireless networks

Aravind B Mohanoor [a], Sridhar Radhakrishnan [a,*], Venkatesh Sarangan [b]

[a] School of Computer Science, University of Oklahoma, 200 Felgar Street, Room 110, Norman, OK 73019, United States
[b] Computer Science Department, Oklahoma State University, Stillwater, OK 74078, United States

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ABSTRACT

Online energy aware routing in wireless networks is the problem of finding energy efficient routes that maximize the network lifetime without the knowledge of future message flows. To maximize network lifetime, the paths for message flows are chosen in such a way that the total energy consumed along the path is minimized while avoiding energy depleted nodes. Finding paths which consume minimum energy and finding paths which do not use energy depleted nodes lead to conflicting objectives. In this paper, we propose two-phased energy aware routing strategies that balance these two conflicting objectives by transforming the routing problem into a multi-metric widest path problem. We find that the proposed approaches outperform the best-known algorithms in the literature. We also demonstrate a simple but insightful relationship between the total energy required along a path and the minimum remaining energy of a node along the path. We further exploit this relationship to show that staying within the solution space of paths with high residual energy *and* low total energy provides much improved lifetimes in general.

1. Introduction

Energy management in wireless networks is of paramount importance due to the limited energy availability in the wireless devices. Since wireless communication consumes a significant amount of energy, it is important to minimize the energy costs for communication as much as possible by practicing energy aware routing strategies. Such routing strategies can increase the network lifetime. In this paper, we focus on developing routing strategies for multiple hop wireless networks where all the nodes are powered by a battery or other external power sources such as solar energy. Usually network lifetime is quantified through the number of packets that can be transferred in the network before the source and destination get disconnected from each other [4,7]. A suitable energy-aware routing strategy for wireless networks is to use those wireless nodes with high energy levels and avoid those with low energy levels.

In developing energy aware routing techniques, wireless networks are modeled as graphs wherein, the vertex represents a wireless device and an edge between two vertices indicates that they are in direct communication range of each other. The weight on a vertex indicates the residual energy available at that wireless node and the weight on an edge (u, v) represents the amount of energy required by node u (resp. v) to transmit one unit of data to node v (resp. u). The *residual energy of a path* is defined as the minimum energy level of any node in the path (referred to as metric 1 in our work). The max–min routing paradigm suggested in the literature [1,4,9] aims to maximize the network lifetime by finding the path where the residual energy is the maximum and forwards packets through this path termed as the *maximum residual energy path*. The *energy consumed along a path* (or simply the *energy of a path*) is the sum of the weights on the edges along the path (referred to as metric 2 in our work). While some defining characteristics of wireless networks, such as lossy links, non-uniform transmission range etc. cannot be completely described by this somewhat idealized graph model it can be used as a good starting point for estimating lifetimes. Also, we are interested in maximizing the lifetime which can be achieved,

* Corresponding author. Tel.: +405 325 1867.
E-mail addresses: aravindmc@ou.edu (A.B Mohanoor), sridhar@ou.edu (S. Radhakrishnan), saranga@cs.okstate.edu (V. Sarangan).

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and the more realistic network models are unlikely to improve on these bounds. That is, the realistic network models typically provide a smaller value of the computed lifetime when compared to the more idealistic model we use, and we are interested in finding lifetimes which are as close as possible to the maximum theoretically achievable value.

Notable routing strategies which utilize the concept of the residual energy (either directly or indirectly) proposed so far include MMBCR [9], MRPC [1] and max–min zP_{min} [4]. These research works also caution that merely using the residual energy strategy may lead to higher energy consumption in the network, since the energy consumed along the data forwarding path is not taken into consideration. They suggest that a good energy-aware routing technique should balance two different goals: choosing a path with maximal residual energy and choosing a path with minimal energy consumption. We note that the residual energy along a path is a concave metric[1], whereas the energy consumed along a path is an additive metric.

In this paper, we present three polynomial time combinatorial techniques which can provide a good balance between metrics 1 and 2. The first technique, called the shortest widest path, first maximizes the concave metric (the residual energy of a path) and then minimizes the additive metric (energy consumed along a path). The second technique, which we call the shortest width constrained path, finds paths with a suitably high residual energy (which may not be the maximum), and then minimizes the energy consumed along such a path. Lastly, our third approach (shortest fixed width path) is similar to the second approach in the sense that it finds a minimum energy path among the paths that have a high residual energy. However, unlike the shortest width constrained path, it does not change the residual energy with each route calculation; the residual energy level is changed only when it becomes infeasible to find paths between the source and the destination at the current residual energy level. Our simulation studies show that the performance of the proposed techniques is superior to that of the best known routing approach proposed in the literature [7]. We also discuss the performance of our proposed algorithms in a distributed setting. Even if the nodes lack an accurate global knowledge of the instantaneous node energy levels, we find that the two phased routing techniques perform reasonably well. We also find that the proposed distributed techniques outperform the distributed implementation (that we have developed) of the algorithm proposed by Park and Sahni [7].

The paper is organized as follows. Section 2 provides an overview of the related work. Section 3 provides the definition of the network lifetime problem as well as our basic solution. In Section 4, we deduce a relationship between the residual energy of nodes along a path and the minimum energy for a given residual energy value. In Section 5, we describe two other solutions which may be considered derivatives of our basic solution. Section 6 compares the performance of our basic algorithm with other approaches on a benchmark topology to show that using the widest path (also called as max–min) approach usually improves the network lifetime. We use empirical evaluations to discuss the performance of our three solutions on general topologies in Section 7. We describe the distributed implementations of the solutions we propose, and their performance, in Section 8. We conclude our discussion in Section 9.

2. Related work

We are interested in lifetime maximization using centralized approaches. Localized algorithms for the lifetime maximization problem have been proposed in the literature under some restricted models. For example, Madan and Lall [6] propose a linear programming based approach for lifetime maximization where the information generation rate is assumed to be constant. Also, Zussman and Segall [11] have proposed localized algorithms for the anycast routing model for emergency network applications. In the centralized case, notable routing strategies which utilize the concept of the residual energy (either directly or indirectly) include CMMBCR [9], max–min zP_{min} [4] and CMRPC [1]. The pioneering work done by Toh et al. [9] establishes multiple formulations for the online energy aware routing problem, of which CMMBCR (conditional min max battery capacity routing) is shown to be better than the remaining approaches. CMMBCR uses minimum energy paths in the first phase, and then shifts to paths with maximum residual energy after node energy levels in the network fall below a certain threshold.

Li et al. [4] describe the max–min zP_{min} algorithm. The max–min zP_{min} algorithm attempts to balance metrics 1 and 2 by calculating a path based on the residual energy levels, but then rejecting any path whose total energy is more than a factor z times the minimum energy path. The quality of the solution provided by the max–min zP_{min} algorithm depends on the empirically generated parameter z, and this does not always provide an optimal solution.

The CMRPC algorithm [1], which is similar to CMMBCR algorithm proposed in Toh et al. [9], uses the residual 'packet capacity' instead of the residual energy for optimization. The residual packet capacity denotes the capacity of each edge in the graph based on the residual energy, the communication cost of the edge as well as the initial energy levels.

Chang and Tassiulas [2] combine metrics 1 and 2 into a single metric and run Dijkstra's algorithm on this new metric. While it is a good heuristic, this method does not actually optimize either metric and makes their approach closely dependent on the empirical values assigned to the parameters used as power terms in the combined metric.

Park and Sahni [7] present the online maximum lifetime (OML) heuristic, which is an enhancement of the CMAX algorithm presented by Kar et al. [3]. OML initially removes edges with low residual energy from the graph. The edge weights are then modified such that a high cost (and thus a heavy penalty) is associated with edges having low residual energy or high communication cost. Dijkstra's algorithm is run on the modified graph such that the paths found usually use nodes with high energy levels and edges with low energy costs. They report that OML gives the best network lifetime among all routing approaches in the current literature.

[1] For definitions of concave and additive metrics, see Wang and Crowcroft [10].