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Evolutionary multi-path routing for network lifetime and robustness in wireless sensor networks

Alma A.M. Rahat*, Richard M. Everson, Jonathan E. Fieldsend

Department of Computer Science, University of Exeter, United Kingdom

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ABSTRACT

Wireless sensor networks frequently use multi-path routing schemes between nodes and a base station. Multi-path routing confers additional robustness against link failure, but in battery-powered networks it is desirable to choose paths which maximise the overall network lifetime — the time at which a battery is first exhausted. We introduce multi-objective evolutionary algorithms to find the routings which approximate the optimal trade-off between network lifetime and robustness. A novel measure of network robustness, the *fragility*, is introduced. We show that the distribution of traffic between paths in a given multi-path scheme that optimises lifetime or fragility may be found by solving the appropriate linear program. A multi-objective evolutionary algorithm is used to solve the combinatorial optimisation problem of choosing routings and traffic distributions that give the optimal trade-off between network lifetime and robustness. Efficiency is achieved by pruning the search space using k-shortest paths, braided and edge disjoint paths. The method is demonstrated on synthetic networks and a real network deployed at the Victoria & Albert Museum, London. For these networks, using only two paths per node, we locate routings with lifetimes within 3% of those obtained with unlimited paths per node. In addition, routings which halve the network fragility are located. We also show that the evolutionary multi-path routing can achieve significant improvement in performance over a braided multi-path scheme.

1. Introduction

This paper examines the use of evolutionary algorithms to find routings in low-power wireless sensor networks that simultaneously optimise the network lifetime and overall network robustness.

Wireless sensors are autonomous devices that measure environmental parameters, such as temperature and humidity. In sensor networks many such devices are distributed over a wide area. Generally these sensors periodically report data back to a central base station, often employing a mesh network topology, in which each device is a node, to extend the range of the network. They are widely used in remote monitoring applications due to ease of installation and the ability to monitor areas that are difficult to access. Inevitably, such applications require these sensors to be battery powered. In addition to powering the sensors themselves, transmission and reception costs are frequently major drains on the batteries. As such, it is important to choose paths from each sensor to the base station that preserve the life of the batteries. Using paths that on average use the least energy can be detrimental to a group of nodes that relay the most paths [1]. We therefore focus on optimising the lifetime of the node that first exhausts its battery; this is the *network lifetime* — the time when the network first needs manual intervention to change a battery [2,3].

Unpredictable and dynamic radio environments, leading to occasional link failures, are inevitable in wireless sensor network (WSN) deployments. The traditional routing approaches deployed in generic wired or wireless networks to achieve network robustness may not be feasible, primarily due to energy, computational and storage limitations at sensor nodes [4,5]. Many existing routing approaches in WSNs consider single-path routing schemes — a single path from each source node to the base station — due to their simplicity and efficient resource utilisation. In case of link failure the single-path routing can be re-planned or re-optimised and the network reconfigured accordingly (see for example [6]). An alternative, which allows receipt of at least partial information during link failure, is to use a multi-path routing scheme in which each source node uses a number of paths to send data to the base station. In such a scheme each node sends a proportion of its messages via each of the available paths; only one path is used for each individual message, so if a link fails the proportion of messages sent via the other routes will be received successfully. Such multi-path routing has been shown to be both fault tolerant through the use

* Corresponding author.
E-mail address: a.a.m.rahat@exeter.ac.uk (A.A.M. Rahat).

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of alternative paths and energy efficient through load balancing [4,7]. As we discuss in more detail in Section 2.3, current measures of robustness generally consider the paths available to each source node, without accounting for the effect on network robustness that results from failure of a link that is used by paths from multiple source nodes. In this paper we therefore quantify the network robustness in terms of the maximum expected data loss (across the entire network) that would occur in the event of a link failure.

Although multi-path routing is beneficial for achieving network robustness, it is likely to have deleterious effects on battery life because it utilises additional links. We therefore propose evolutionary algorithms to locate routes that find routings which approximate the optimal trade-offs between network lifetime and robustness.

Simultaneously improving both network lifetime and robustness is pivotal for devising a successful multi-path routing scheme in WSNs. Current routing protocols treat this two-objective optimisation problem as a single objective problem. For instance, Yahya et al., define a composite weighted link cost combining energy, available buffer storage, and radio interference where the relative importance of the cost are controlled with weights [8]. A preferred path is constructed based on this link cost, and when the cost becomes expensive beyond a threshold, a new path is used to send data. A similar strategy is adopted in [9]. However, the trade-off between different possible routings is not explored. The optimal trade-off front, also known as the Pareto front, consists of the routings which are not *dominated* by any other routing [10]; that is, routings for which there is no other routing with better network lifetime and robustness. *Evolutionary algorithms* (EAs) are an efficient method of finding the Pareto front. They deploy a population of possible routings and are capable of evolving a set of solutions that well approximate the optimal trade-off front [10].

Most current EA-based multi-objective routing optimisation approaches consider single-path routing schemes to optimise various objectives: energy efficiency, network lifetime, latency, robustness, expected transmission count, etc. [11–14]. Here we describe a framework for multi-path routing optimisation with two objectives: maximise network lifetime and maximise robustness, and estimate the optimal trade-off front. This approach can achieve solutions with network lifetimes close to the theoretical maximum network lifetime (when no constraint on the number of routes per node is imposed) as presented in [1], and a range of solutions representing various levels of robustness. The major contributions of this paper can be summarised as:

- We describe a hybrid evolutionary search procedure to approximate the optimal trade-off between network lifetime and network robustness.
- We introduce a novel robustness measure (the *fragility*) of multi-path routing schemes to quantitatively analyse and compare the robustness of different multi-path routing schemes. The fragility accounts for the effect of failure of a link shared between multiple source nodes.
- We show how the proportion of time for which each path should be used in a multi-path scheme may be determined by an appropriate linear program to optimise either network lifetime or robustness.
- Novel search space pruning methods, based on braided and edge disjoint paths, are used to speed the evolutionary search by restricting the search space to regions likely to contain good solutions.
- The proposed methods are illustrated in a real network deployed in Victoria & Albert Museum, London, UK, and successfully locate a wide range of robust multi-path routing schemes with long network lifetimes and greater robustness, surpassing the performance of single-path routing schemes.

The rest of the paper is structured as follows. In Section 2 we describe our network model and the associated formulation of network lifetime and robustness. Section 3 describes the multi-objective problem to be optimised and in Section 4 a hybrid evolutionary algorithm to solve it is presented. Search space pruning, key to the efficiency of the evolutionary algorithm, is discussed in Section 4.1. The method is evaluated and compared with popular methods on synthetic and real networks in Section 5. Related work is discussed in Section 6. Finally, conclusions are drawn in Section 7.

2. Network model, lifetime and robustness

In this section, we present a model for WSNs with multi-path routing and formulate network lifetime and robustness as objectives to be optimised.

2.1. Network model

We consider a communication protocol in which all nodes periodically (e.g., once every minute) send their sensed data to the base station, potentially by relaying a message through one or more nodes. Such data reporting periods are repeated throughout the network lifetime: the time before which a node first exhausts its battery. This scenario is most common in industrial applications, especially for constant monitoring of locations.

Once a connectivity map, showing which nodes may communicate with each other, has been established, routing is performed under the assumption that links are reliable. Generally, pairs of nodes are configured to use the most energy efficient settings that allow reliable communication. Usually energy efficient links correspond to high baud rate and low transmission power.

Note that we used very low power sensor nodes in this paper. As such the frequent *pinging* in connectivity discovery is prohibitively expensive. Therefore, the connectivity discovery process is only triggered in case of establishing the network for the first time or severe deterioration in performance. Furthermore, nodes are not capable of performing route calculations due to very limited computational resources. Thus routing calculation and decisions are performed at the mains powered base station in a centralised manner as configuring the sensors infrequently over the radio link is relatively cheap (for instance, in the real world implementation we consider here, each network configuration cycle costs approximately 0.1% of the total battery energy per node).

We deem the hardware to be reliable, and thus node failure is a rare event that necessitates replacement of the node. On the other hand, the radio environment is seldom constant and links may occasionally fail due to changing atmospheric conditions, the passage of people, radio interference, and so on. One mechanism to combat the intermittent failure of links is to provide more than one path from each node to the base station. Each node then splits its traffic between the available paths, sending a proportion of messages via each of the available paths; exactly one path is used on each data reporting cycle, rotating between the available paths. Thus if there is a failure on one path, messages sent via other paths will still be received, providing at least partial information. We call the proportion of time that a particular path is utilised the *active time share* for that path.

A WSN is represented as a network graph, $G = \{V, E\}$, where V is a set of N sensor nodes v_i plus a base station node v_B, and E is the set of edges, describing with which other nodes each node can communicate [15]. Fig. 1 illustrates a multi-path routing in which there are two routes from node v_i to the base station v_B: $R_{i1} = \langle v_i, v_j, \dots, v_B \rangle$ and $R_{i2} = \langle v_i, v_k, \dots, v_B \rangle$. We denote by τ_{id} the active time share of path R_{id}, namely the proportion of messages sent by v_i via route R_{id}. Clearly, $\tau_{id} \geq 0$ for all i, d and $\sum_d \tau_{id} = 1, \forall v_i \in V$.