Sensor network routing algorithms for realistic battery models

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Abstract

Sensor networks are expected to revolutionize information gathering, processing and dissemination in many diverse environments. The most important factor in the design of sensor networks is the conservation of battery capacity. In order to maximize battery life, it is desirable that accurate battery models be used in designing power-efficient algorithms for sensor networks. Surprisingly, almost all existing work uses unrealistic battery models which assume that a battery is a "bucket" filled with a number of units of energy and that each packet removes a fixed number of units. Real batteries are much more complex, and display several non-ideal properties. We believe that the performance of sensor network protocols can be improved by incorporating battery characteristics. The objective of this paper is to provide evidence for this hypothesis by considering the problem of routing. Specifically, we show that algorithms designed using more complex battery models perform better in real networks.

In this paper, we model arguably the most important non-ideal property of real batteries, viz., the charge recovery effect – battery capacity actually increases when it is allowed to rest for some time. We develop a simple model for the charge recovery effect, and then propose a routing algorithm based on it. Our algorithm makes use of two simple, intuitive objectives: each battery should be allowed to rest between uses if possible, so that its capacity regenerates, and that the communication load between two nodes should be distributed over multiple paths between them. While it would be nice to balance the communication load between multiple paths, generating edge or node disjoint paths is a computationally hard problem. We address this problem by generating multiple paths using existing algorithms for braided multipaths. This can be done efficiently and produces paths that are mostly disjoint. We compare (using simulation) our algorithm with the well known directed diffusion algorithm which uses a single path for all packets. Our experiments show that our algorithm outperforms directed diffusion in terms of the minimum residual battery capacity in all the situations considered. The relative performance of these algorithms in terms of the average residual battery capacity is heavily dependent on the battery characteristics.

1 Introduction

Sensor networks are made of very simple nodes that have a processor, memory, wireless communication capabilities, sensor(s) and a power source (batteries) on-board. The sensor nodes are deployed in the environment being studied and they self-organize into a coherent network. Typically, the network is connected to the outside world through (and can be queried using) one or more gateways. The design of efficient protocols for sensor networks has been a very active research are in recent years. It is believed that sensor networks will revolutionize information gathering, processing and dissemination in diverse and hostile environments.

By far the most important factor in the design of sensor network protocols is the conservation of battery power, since sensor nodes run off of (typically small) batteries. It is therefore, imperative that accurate battery models be used in designing power-efficient algorithms for sensor networks. Surprisingly, almost all existing work uses unrealistic battery models. These models assume that a battery is a "bucket" filled with a number of units of energy and that each packet removes a fixed number of units. Real batteries are much more complex, dynamic systems that have several different phenomena existing simultaneously. It is our belief that the use of more complex battery models will result in algorithms that perform better in real networks than existing algorithms. While we believe that this is true in multiple layers, we deal with only the network layer here. This paper describes our work in progress and is intended to argue that better routing algorithms can be designed by using realistic battery models. Unlike existing work on battery-aware routing [1, 2, 3], we do not use battery power-related cost functions in existing shortest-path algorithms. Instead, we demonstrate that a simple, distributed multipath routing algorithm designed to utilize battery characteristics conserves battery power better than existing algorithms like directed diffusion. Our work provides a new reason for not using a single path for routing packets between a source and a destination as done by existing algorithms like directed diffusion.

1.1 Routing in Sensor Networks

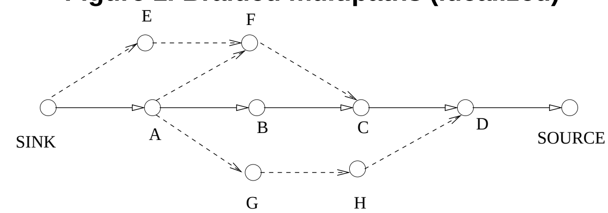
Routing algorithms used in traditional wired networks are unsuitable for sensor networks in many ways. First, the assumption that every node has a globally unique identifier is unrealistic in large sensor networks. Second it is often desirable and efficient to address nodes in a *data-centric* manner – i.e., using attribute-value pairs. Finally, highly centralized shortest path algorithms like Dijkstra's algorithm are not suitable for sensor networks. Arguably the best known routing algorithm for routing in sensor networks is called directed diffusion [4]. We describe the basic idea behind this algorithm very briefly below.

Sink nodes propagate their interests (the data they wish to receive), typically by some kind of flooding. A source that has this kind of data then sends data along a number of paths that have high interest *gradients*. The sink then identifies a primary path and an alternate path out of these paths. Data is sent along the primary path and the alternate path is maintained by sending packets periodically for the purposes of fault tolerance. This algorithm is fully distributed, and works well for a variety of sensor networks.

It has long been known that using a single path for routing packets, while quite appropriate for wired networks, is bad for sensor networks since they drain the batteries of the nodes on the primary path fast. In fact, the original directed diffusion paper [4] points this out and observes that directed diffusion can be modified to use multiple paths in order to balance the communication load over several paths. Subsequently, many papers (e.g. [5, 6, 7]) propose the use of multiple paths (also called multipath routing) for sensor networks or more generally for ad hoc wireless networks. These and other papers list several nice properties of multipath routing, including load balancing and fault-tolerance. Balancing the communication load results in battery conservation. In this paper, we provide an additional advantage of multipath routing by showing that a round-robin scheduling among different paths leads to additional power savings due to specific battery characteristics.

We focus on multipath routing next. While the idea of using multiple paths is very appealing, the generation of multiple disjoint paths is a computationally difficult problem. Further, many algorithms are either centralized or need a lot of communication between nodes – both being undesirable for sensor networks. A very efficient algorithm was proposed by Ganesan et al [5] for generating paths that are mostly disjoint. These paths are called *braided multipaths*. Apart from being computationally efficient, the algorithm in [5] is completely distributed. While the authors observed that braided multipaths provided considerable greater resilience to node failures and better battery conservation, the paper did not focus much on the load balancing aspects of the proposed algorithm.

Figure 1. Braided multipaths (idealized)



The basic idea behind braided multipaths is shown in figure 1. Like directed diffusion, this algorithm requires sinks to flood their interests and sources to identify high gradient paths and send packets along them. However, unlike in directed diffusion, a source reinforces a primary path but no alternate path. Instead, each node on the primary path reinforces an alternate path to another node in the path. For example in figure 1, node A finds an alternate path to C via F. Using the terminology in [5], this produces *localized braids*. The rules for generating localized braids can easily be generalized to find more alternate paths. For example, in figure 1 node A might discover an alternate path to D via G and H. These are called *idealized braids* in [5].

Ganesan et al [5] also describe a set of paths called *perfect braids* that guarantee an exponential number (in the umber of nodes) of disjoint paths. Clearly, the computation of an exponential number of paths is prohibitively expensive, and it is difficult to compute them in a distributed manner. Therefore, we use the idealized braids in our routing algorithm.

We now discuss briefly some aspects of real batteries that are relevant to our work.

1.2 Realistic battery models

Although we tend to think of batteries as a simple, ideal power source, real-life batteries are complicated physical devices with several non-ideal properties. Some of the important ones are listed below.

- The voltage of a battery depends on its state of discharge.
- If the requested current exceeds specifications, the battery delivers a smaller amount of energy. This is called the *rate capacity* effect [1].
- The decrease of capacity of a battery depends on the discharge rate.

- Batteries display a *charge recovery effect* – the capacity actually increases when the battery is allowed to rest for some time.[1]
- The temperature at which a battery operates affects the capacity of a battery.
- Rechargeable batteries lose capacity with each recharge – this is called *capacity fading*.

It should be clear from the above list that complex dynamic models are needed to accurately model and/or predict battery performance. Indeed, several very sophisticated models have been developed for this purpose. The interested reader is referred to a nice survey of these models in [8].

Since our focus in this paper is on sensor networks, we only study the most important characteristics of batteries for our purposes. We do not attempt to model rechargeable batteries since they are not typically used (yet) in sensor networks. The operating temperature of a battery is very hard to model since we do not know the environment under which a battery may be operating. Therefore, we concentrate on modeling the charge recovery effect in this paper.

Our battery model assumes that the battery discharges at a rate $d(t, V(t))$ and recharges at a rate $r(t, V(t))$ where $V(t)$ is the voltage of the battery at time t. In general, different batteries will have different functions $r()$ and $d()$. We study the performance of our routing algorithms for a simple intuitive candidate function

$$r(t) = c_1 e^{-c_2 t}, \tag{1}$$

where c_1, c_2 are constants. This function captures the empirically observed phenomenon that the charge recovery effect is more significant at first and tapers off with time. The precise values of c_1, c_2 are dependent on the specific technology being used. We use a discharge model $d(t, V(t)) = c_3$ in this paper. This implies that the battery discharge depends on packet size but not current voltage and past usage. We emphasize that these choices do not model all battery technologies and that we use them only to support our hypothesis that better routing algorithms can be designed by using battery characteristics.

1.3 Battery-aware routing

There are several techniques for designing battery-aware routing algorithms. The most intuitive approach is to use a shortest-cost path algorithm (e.g., Dijkstra's algorithm, the distance vector algorithm) in which the cost is a function of the battery levels. In Section 1.5, we listed existing papers that use this approach. We feel that this approach is unsuitable for sensor networks since centralized algorithms (e.g. Dijkstra's algorithm) require that each node have an accurate estimate of the state of the batteries in the entire network, and distributed algorithms like the distance vector algorithm require frequent updates of the routing tables. Both of these are likely to be prohibitively expensive for sensor networks. In Section 1.5, we survey some approaches for battery-aware routing that propose less expensive variations of this idea.

In this paper, we take a different approach. In our view, a battery-aware routing algorithm is one that is designed factoring in the battery characteristics outlined in section 1.2. Clearly, the routing algorithm must allow nodes periods of rest between transmissions (as far as possible) in order to maximize the benefits of the charge recovery effect. There are several ways in which this can be done. Since the shortest path between two nodes may be unique, we relax the requirement for shortest-cost paths. Our objective is to design an algorithm that generates several alternative paths between a source and a destination and then sends packet in a round robin manner on these routes. Ideally, one would want the paths to be node-disjoint, but since computing node-disjoint paths is a computationally hard problem, we relax this requirement as well.

1.4 Connections to load balancing

This paper proposes dividing the communication load between alternative paths in order to allow periods of rest for nodes even in the presence of heavy traffic. This suggests a strong connection to load balancing in sensor networks. In fact, we require a very strict variant of load balancing that is not required by algorithms designed for traditional battery models. For traditional models, it is enough for the total load to be divided among several paths. Thus, it is enough to distribute the total number of messages equally among alternate paths. In contrast, we wish to take advantage of the charge recovery effect and therefore require that the load balancing be done at the *packet level*. Not surprisingly, our algorithm makes use of braided multipaths, which were proposed to have strong load balancing properties.

1.5 Related work

There has been a lot of work in routing in sensor networks. We do not attempt an exhaustive survey here; instead, we refer the interested reader to the survey [9]. In this section, we outline some of the papers relevant to this work.

Proposed battery models: Battery models have not received very much attention in the literature, considering the huge scope of batteries in virtually all areas of electronics. Rao et al [8] present a nice survey of the characteristics and models of different battery technologies. Benini et al [3] focus only on discrete-time models and their use in low-power electronics. Martin et al [10] quantify the deviation from

[1] This effect is well-known to users of mobile phones – the talk time values advertised for mobile phones assume periodic use and are not valid when the phone is in continuous use.

ideal behavior in different batteries and study their impact on wearable computers. Lahiri et al [11] survey different models for batteries and highlight issues in system design, including battery scheduling and management.

Routing in sensor networks: The older routing protocols for sensor networks used single paths for routing. Directed diffusion is a good example of this. More recent protocols proposed multipath routing [5, 6, 7]. We have discussed [5] in section 1.1. We discuss the other two papers below.

In [6], the authors propose a somewhat different extension of multipath routing called meshed multipath routing. However, this paper focuses on a different problem, viz., the use of replicated packets on alternate paths to ensure high resilience to node failures. They propose and evaluate different strategies for forwarding the (multiple copies of) packets in their routing algorithms. In [7], the authors proposed a multipath extension of the well-known source routing algorithm DSR.

Battery-aware routing: Chiasserini and Rao [1] propose using shortest path algorithms that use a path cost computed from the battery levels of nodes on the path. The battery model used incorporates the rate capacity effect and the charge recovery effect and is first proposed in [2]. It argues that computing the minimum cost path from all possible ones is computationally expensive, and so k paths are chosen at random and the path that has the minimum cost among these k paths is chosen.

1.6 Our contributions

In this paper we propose new routing algorithms that are designed taking into account more realistic battery models. We demonstrate using simulations that our algorithms outperform several existing algorithms on the more realistic battery model used in this paper. Our algorithm makes use of two simple intuitive objectives:

- Each battery should be allowed to rest between uses if possible, so that its capacity regenerates and its life is extended due to the *charge recovery effect*.
- Many paths between a pair of nodes should be used, and the communication load should be distributed over these paths, so that the reduced use of each node results in extended battery life.

The basic idea behind our algorithm, and that achieves both the above objectives is to use multiple paths between a source and a destination. However, the obvious scheme of generating all pairs of paths and balancing the load between them is not efficient, since there are potentially an exponential number of paths between two nodes. Further, these paths are not edge or node disjoint. Generating disjoint paths is a computationally hard problem. We solve this problem by making novel use of braided multipaths [5, 6].

2 Our routing algorithm

The basic steps of our algorithm are as follows.

1. Sinks propagate (using flooding) their interests in the network, similar to directed diffusion. Sources receiving this message send data along high gradients.
2. A primary path and braided multipaths are generated using a generalization of the algorithm in [5]. We generate k braids from each node.
3. When packets are sent, each node on the primary path schedules packets to outgoing multipath edges in a round robin manner. Nodes not on the primary path simply forward packets along the braid.

We point out that this algorithm does localized routing, i.e., the next hop of a packet is determined at the current node. The algorithm is also simple to implement and requires no centralized coordination. We remind the reader that the paths followed by successive packets are not guaranteed to be disjoint (and in fact are not) but it is unlikely that the same node is used repeated in different braided paths.

We investigated a source routing algorithm in which the braided multipaths are used at the source to get perfect braids. The entire path of a packet is then encoded in each packet. We simulated the reduction of packet sizes due to reduction of header size as the packet progresses through the network and the nodes already traversed are removed from the header. The performance did not justify the extra computation and communication costs involved.

3 Performance evaluation

The objective of this section is to demonstrate that battery-aware routing algorithms outperform other routing algorithms. We compared our algorithm with directed diffusion [4], since it has been shown to perform well in different scenarios and conditions.

In this paper, we simulated only the routing algorithms using a homegrown simulator written in C++. The rationale for this was to eliminate the effects of the MAC layer and focus solely on the effect of the routing algorithm used. We expect that our results will not be useful in predicting when the battery in a node will die, but it will allow us to decide if a routing algorithm conserves battery power better than another.

We simulated a rectangular 2-dimensional sensor field where sensors were placed randomly. The sink is placed in a corner of the field. The nodes are assumed to be connected if they are within radio range of each other. For simplicity, we assume radio range to be fixed and do not model fading.

We simulated a sensor field of size 10 x 15 (in units of radio range). We distributed 450 sensors in the field. The battery capacity is initialized to 10,000,000 units and we assumed that each transmission takes 20,000 units of energy and each reception takes 1,000 units for normal packets. For smaller packets used to maintain alternate paths, we assumed that each transmission takes 1000 units and each reception takes 50 units of energy. The parameter c_1 (in equation 1) was set to 100 and c_2 was set to 1. We ignored other sources of battery drain, since we expect the communication to consume most of the power. All these choices are technology-dependent and were made to simulate a realistic situation.

We used multiple sources which were spread randomly in the field. All communication was from source to sink in our experiments – i.e., each packet originated at some source, and passed some nodes en route to the sink. We assumed that the sensors expended a significant amount of energy in transmitting a packet and considerably less so in receiving one. We assume that no energy is consumed in idle wake states. This is not true for real sensors but it suits our purposes since our aim is to distinguish between routing algorithms rather than predicting the lifetime of a node or network.

3.1 Our metrics

Since our algorithm tries to maximize battery power, our metrics measure battery levels. Specifically, we study the minimum energy level across all the sensors, as well as the average energy level of the sensors.

Since our routing algorithm attempts to balance the communication load over different paths, intuitively, we expect that it improves the minimum energy levels of sensors. It is not as obvious that our algorithm should also improve the average energy levels, since the paths chosen by our routing algorithm are not always shortest paths.

3.2 Experimental Results

Our results are presented in Figures 2 and 3. The curves marked "traditional" use the traditional battery model where the battery is a bucket of energy units and the rate of sending/receiving packets does not affect the amount by which battery capacity decreases. The curves marked "new" incorporate the charge recovery effect. Both curves are obtained by averaging 20 runs of the algorithm.

Our simulation results illustrate two basic points: first, our algorithm always improves the minimum energy levels, as is expected; second, the average energy is sensitive to the extent of the charge recovery effect, specifically the parameter c_2 in equation 1. Setting c_1 to a high value and/or c_2 to a low value allows much more capacity to be recovered and our algorithm produces much higher average residual energy levels than directed diffusion in this scenario. Conversely, setting c_1 to lower values and/or c_2 to higher values make the average residual energy under directed diffusion to be superior to that produced by our algorithm. The results presented in this paper are for the latter scenario.

Figure 2. Minimum residual energy

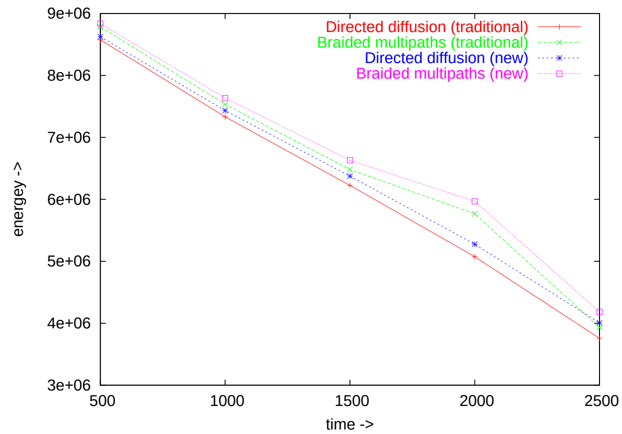
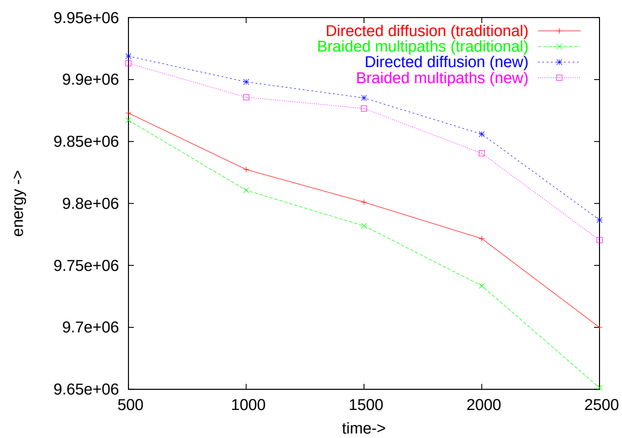


Figure 3. Average residual energy



We investigated the effect of k, the number of multipaths at any node on the primary path. Our experiments showed that $k = 3$ gave the best performance. Our results are for this value of k.

4 Discussion

This paper presents work in progress and therefore leaves a number of loose ends. We discuss some of these below.

Effect of specific technologies: Batteries vary widely in both capacity and charge recovery characteristics. Also, the power used for reception and transmission depends on the radios being used. While we expect our results to be valid for most reasonable models, it is possible that there are scenarios where they are not.

Effect of node placement on our algorithm: The performance of our algorithm depends on the availability of multiple, alternate, mostly disjoint, paths between a source and a sink. The placement strategy we used in our experiments satisfied these requirements and therefore our algorithm outperformed algorithms that use a single path. Alternate paths satisfying these requirements are not available in other placement schemes. We are investigating the use of analytical techniques to characterize placement schemes in terms of the availability of alternate paths satisfying our requirements.

Effect of a hierarchical organization: This paper assumes a flat network. The availability of alternate paths may be affected by hierarchical networks. We chose not to focus on hierarchical topologies in this paper, partly because hierarchical networks with fixed cluster heads require that the cluster heads have higher battery capacity. Hierarchical network architectures with rotating cluster heads (e.g. LEACH [12]) do not have this requirement. We expect the basic idea of using multiple paths to still be useful in this model but multipath generation requires different ideas and is deferred to future work.

Effect of the medium access control algorithm: Although we have abstracted away the medium access control algorithm, the MAC layer clearly impacts the battery performance since it schedules sleep periods and therefore allows the battery to regenerate. We expect our qualitative results (i.e., the ranking of the performance of the different algorithms) to be valid for MAC layers that have fixed sleep periods. We do not know if our results hold for adaptive MAC protocols (e.g., those that allow heavily depleted nodes to sleep more). We plan to implement our algorithm in ns-2 [13] and study the effect of the MAC layer on routing performance.

5 Conclusions and Future Work

In this paper, we have showed that routing algorithms that are designed using more realistic battery models perform better. In particular, we argue, using realistic battery models, that batteries benefit from a very strong variant of load balancing. We demonstrate that a simple, distributed routing algorithm that chooses between available paths in a round-robin manner outperforms the well-known directed diffusion algorithm [4] in terms of minimum residual energy and is close to it in terms of average residual energy. Thus, our work provides an additional compelling reason for using multiple paths for routing between a pair of sensor nodes. A desirable side effect of our algorithm is that it provides very good resilience to node failures or battery expirations. We did not focus on this aspect since other papers [5, 6] have already reported this property of multipath routing algorithms.

As pointed out in [5], there are many different ways to generate multipaths, including the algorithm proposed in [6]. We are investigating the effect of other multipath algorithms on battery performance.

Finally, we are working to incorporate realistic battery models into the design of other sensor network protocols, especially the MAC protocol. Intuitively it would make sense to schedule sleep periods of sensor nodes adaptively to take advantage of the charge recovery effect.

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