



Empirical evaluation of the heat-diffusion collection protocol for wireless sensor networks



Pradipta Ghosh^{a,*}, He Ren^b, Reza Banirazi^a, Bhaskar Krishnamachari^a, Edmond Jonckheere^a

^aMing Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, California, USA

^bElectrical Engineering, Stanford University, Stanford, California, USA

ARTICLE INFO

Article history:

Received 4 September 2016

Revised 14 August 2017

Accepted 19 August 2017

Available online 24 August 2017

ABSTRACT

Heat-Diffusion (HD) routing is our recently-developed queue-aware routing policy for multi-hop wireless networks inspired by Thermodynamics. In the prior theoretical studies, we have shown that HD routing guarantees throughput optimality, minimizes a quadratic routing cost, minimizes queue congestion on the network, and provides a trade-off between routing cost and queueing delay that is Pareto-Optimal. While striking, these guarantees are based on idealized assumptions (including global synchronization, centralized control, and infinite buffers) and heretofore have only been evaluated through simplified numerical simulations. We present here the first practical decentralized version of HD algorithm, which we refer to as Heat-Diffusion Collection Protocol (HDCP), for wireless sensor networks. We present a thorough evaluation of HDCP based on real testbed experiments, including a comparative analysis of its performance with respect to the state of the art Collection Tree Protocol (CTP) and Backpressure Collection Protocol (BCP) for wireless sensor networks. We find that HDCP has a significantly higher throughput region and greater resilience to interference compared to CTP. However, we also find that the best performance of HDCP is comparable to the best performance of BCP, due to the similarity in their neighbor rankings, which we verify through a Kendall's-Tau test.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Low power wireless sensor networks tend to be used for low-data rate applications. However, their scaling in terms of network size as well as operation under low duty cycles is often limited due to bandwidth constraints. Routing algorithms that can utilize the full bandwidth capacity of the network are therefore very important and continue to be a subject of research and development.

Throughput Optimality: In network theory, the ability to fully utilize the available bandwidth in a network is tied to the notion of throughput optimality. An algorithm is said to be throughput optimal if it has the ability to maintain stable queues at any set of arrival rates that could possibly be stabilized by at least one algorithm. The Back-Pressure (BP) routing algorithm [1] was the first queue-aware routing protocol to offer in theory a throughput optimality guarantee under general link state and traffic conditions. It has been translated to practice in the form of the Backpressure Collection Protocol (BCP) [2] for wireless sensor networks,

which was shown to provide improved capacity and robustness to link dynamics compared to the state-of-the-art queue-unaware tree-based routing protocols (e.g., the well known Collection Tree Protocol, CTP [3]).

What is Heat Diffusion (HD) algorithm? The Heat Diffusion (HD) algorithm [4] is our recently proposed alternate queue-aware throughput optimal routing policy for wireless networks. It is derived from a combinatorial analog of the classical Heat Diffusion equation in Thermodynamics (where queue size is analogous to temperature, and packet flow to heat flow) that takes into account wireless interference constraints. Moreover, in [5] we have shown that the underlying mathematical formalism is also essentially the same as current flows in resistive circuits. Therefore, the link penalties corresponding to resistances can be incorporated into HD routing in a way that allows for minimizing a specific form of average routing cost referred to as the Dirichlet routing cost. The Dirichlet routing cost is defined as the product of a link's cost and square of the respective link's flow rate. Moreover, the HD algorithm also minimizes the overall queue congestion of the network among the class of throughput optimal algorithms that make decision based on only current queue occupancies and link statistics. The HD routing algorithm guarantees to operate on the Pareto boundary if both routing costs and queue occupancies are

* Corresponding author.

E-mail addresses: pradiptg@usc.edu (P. Ghosh), rhilugin@gmail.com (H. Ren), banirazi@gmail.com (R. Banirazi), bkrishna@usc.edu (B. Krishnamachari), jonckhee@usc.edu (E. Jonckheere).

considered in the objective function. We detail the HD algorithm in Section 3.

Motivation of Our Work: In theory, the HD routing algorithm goes beyond just throughput optimality guarantees to provide additional significant improvements in average queue sizes (delay) and average routing costs (such as expected transmission count, ETX¹) compared to traditional Backpressure routing. To date, this HD algorithm has remained a theoretical and idealized construct that requires a centralized implementation. This centralized version requires a complete knowledge of a network and a NP-hard scheduling procedure at each time and assumes that buffer sizes are unbounded at all nodes. What has been missing in the literature is a practical implementation of the HD policy that is distributed and works with finite buffer lengths, and whose performance is studied comprehensively on a real wireless testbed. We seek to address this gap.

Our Contribution: Our contribution in this paper is multi-fold. **First**, we present the first-ever decentralized version of the Heat-Diffusion algorithm and present a Contiki OS [7] based practical protocol implementation for data collection in wireless sensor networks: the Heat Diffusion Collection Protocol (HDCP). This also include practically-motivated enhancements of the original Heat Diffusion algorithm, modifications to the link weight calculations, and a link switching scheme to diversify the link usage. **Second**, we propose and evaluate a new method of dynamic ETX calculation suitable for any dynamic routing algorithm, including the previously proposed BCP [2] as well as HDCP. **Third**, we present and analyze the data collected from an extensive set of practical experiments conducted with HDCP utilizing forty five nodes on a real wireless sensor network testbed. Based on these data, we discuss the variation in the performance of HDCP under different parameters. **Fourth**, we compare HDCP with a Contiki-OS implementation of BCP [2] as well as CTP [3]. We show that on the real testbed, HDCP offers significant improvements in performance over CTP in terms of throughput as well as resilience to external interference and node failures. We also show that the performance of HDCP is similar to BCP, and through evaluation of a Kendall's Tau similarity measure, show that this is due to similar rankings among the neighbors. Finally, we also verify that HDCP performs well with a low power communication stack (CX-MAC, a version of X-MAC[8] that is provided in Contiki, with 5% duty cycle).

Paper Organization: The rest of the paper is organized as follows. In Section 2, we present a brief overview of the existing related works followed by a brief summary of the theoretical HD algorithm in Section 3. We introduce the proposed Heat Diffusion Collection Protocol in Section 4. Section 5 explains the practical implementation details of HDCP for the real experiment based comparative analysis of HDCP presented in Section 6. The similar empirical performance between HDCP and BCP is analyzed and explained in Section 7. Section 8 concludes the paper.

2. Related works

Besides the original Backpressure routing algorithm, other throughput optimal policies [9–11] have also been proposed in the existing network theory literature. The HD algorithm also provides the same throughput optimality guarantee in theory. However, what motivated us to implement HD were the striking additional expected performance capabilities (based on our theoretical results)— that it also offers a Pareto-optimal trade-off between routing cost and queue congestion.

There have also been several reductions of Backpressure routing to practice in the form of distributed protocols, pragmatically implemented and empirically evaluated for different types of wireless networks [2,12,13]. Most relevant to the present work is the Backpressure Collection Protocol (BCP) developed by Moeller et al. [2], the first ever implementation of dynamic queue-aware routing in wireless sensor networks. Our present work is informed by the BCP approach to implement Backpressure routing in a distributed manner, and we also directly compare the performance of the new HDCP protocol with BCP.

Besides BCP, there are a number of other prior works on routing and collection protocols for wireless sensor networks, including the Collection Tree Protocol (CTP) [3], Glossy [14], Dozer [15], Low-power Wireless Bus [16], ORW [17] and Oppcast [18]. We provide a side by side comparison of HDCP with the well-known CTP and BCP protocols. We believe this provides a meaningful comparison with a state of the art minimum cost quasi-static routing protocol as well as a state of the art queue and cost-aware dynamic routing protocol.

In recent years there has been a significant focus in developing networking protocols that are IP-friendly, such as RPL [19]. While the present paper does not focus on providing an IP-compliant version of HD, there is prior work on extending BCP to handle IP packets [20], and we believe that a similar approach could be adopted to enable IP operation for HDCP in the future.

In our prior works, we have presented the idealized Heat Diffusion routing algorithm [4,5]. These are network theory papers that spell out a centralized algorithm, assume global synchronization, assume that at each time step a NP-hard Maximum Weight Independent Set problem can be solved, and that all queues are of unlimited size, and under these assumptions prove various properties of the HD algorithm. The only evaluations presented in these works are idealized MATLAB simulations. This work is clearly inspired by and built up on our earlier works on HD routing but is the first to develop and implement it as a realistic distributed protocol (HDCP) and evaluate it on a real testbed.

3. The heat diffusion routing: theory and concepts

The general idea behind dynamic queue-aware routing algorithms such as the Backpressure [1] algorithm and the Heat Diffusion [4] algorithm is that they do not require any explicit path computations. Instead, the next-hop for each packet depends on queue-differential weights that are functions of the local queue size information and link state information at each node. It is a general assumption in (theoretical) queue-aware routing algorithms such as BP and HD that the networks operate in slotted time. Furthermore, a wireless network is represented as a graph $(\mathcal{V}, \mathcal{E})$ with vertices \mathcal{V} and edges \mathcal{E} . However, the adjacent links or edges of a wireless network cannot be used simultaneously due to many constraints such as interference. In that context, a *maximal schedule* is defined as a set of links such that no two links interfere with each other and no other link can be added to that set without causing interference. We will denote a maximal schedule as: $\pi = \{\pi_{ij} | i \neq j \text{ and } i, j \in \mathcal{V}\} \in \{0, 1\}^{|\mathcal{E}|}$, where $\pi_{ij} = 1$ if the link ij (or link ji) is included in the schedule. The set of all such maximal schedule is referred to as a *scheduling set*, denoted as Π .

The Heat Diffusion (HD) [4] routing has been derived from the combinatorial analogue of classical Heat-Diffusion equation in Thermodynamics. It uses the information about estimated link capacities, $\mu_{ij}(n)$, link cost factor, $\rho_{ij}(n)$, and queue backlogs, $q_i(n)$ $\forall i \in \mathcal{V}$, to make the routing decisions to put f_{ij} packets at each time slot n . The optimization goal of the HD algorithm for a wireless

¹ The expected transmission count (ETX) is a well-known link quality metric in the context of wireless communication which represents the average number of transmissions required for every successful packet transfer [6].

متن کامل مقاله

دریافت فوری ←

ISIArticles

مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات