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A load-balancing routing algorithm for wireless sensor networks based on domain decomposition ☆

Ren-Song Ko

National Chung Cheng University, Department of Computer Science and Information Engineering, Chia-Yi, Taiwan

A R T I C L E   I N F O

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A B S T R A C T

Massively-dense wireless sensor networks (WSNs) may increase the difficulty of designing efficient and optimal routing algorithms. Since, from a macroscopic perspective, the optimal load-balancing routing problem may be formulated as a set of partial differential equations (PDEs), a scalable routing algorithm may be obtained by using WSNs themselves to solve the PDEs numerically, e.g., through the Gauss–Seidel iteration. To accelerate convergence without sacrificing precision, the proposed distributed Multiplicative Schwarz routing (DMSR) algorithm uses domain decomposition to iteratively solve the PDEs. Furthermore, the precision and parallelism may be improved by adapting an appropriately defined iteration order. Algorithm performance is analyzed theoretically for parallelism and errors, and numerical simulation results are presented to assess the efficiency and effectiveness of DMSR in achieving load balancing.

1. Introduction

Advances in hardware miniaturization and wireless communication have made it possible to network a large number of smart sensors on an ad hoc basis to bridge the gap between the cyber and physical worlds. These wireless sensor networks (WSNs) have significant potential for the development of many new applications in monitoring environmental conditions in hazardous or inaccessible places [1]. However, given that all sensors and interconnections need to be considered to determine the best sensor to perform a certain operation, the scale of these WSNs raises challenges for the design of efficient and globally-optimized routing algorithms.

Unlike in many traditional wireless network applications, extending the duration of a WSN function is more important than keeping each node alive. Therefore, it may be preferable to exhaust individual nodes in an attempt to achieve better overall performance. In addition, WSN applications are usually spatially-oriented and spatially close nodes tend to perform identical roles within networks. This high degree of substitutability improves overall application performance by managing networks from a macroscopic perspective, rather than optimizing the performance of individual nodes.

By ignoring microscopic details, the global load-balancing routing problem of WSNs may be formulated as a set of partial differential equations (PDEs) [2]; hence the derived routing algorithm, namely the distributed Gauss–Seidel iteration (DGSI) algorithm, coordinates sensors to iteratively solve the PDEs using the finite-difference method (FDM) and the Gauss–Seidel iteration (GSI) method. The solution is then used to provide guidance for information routing.

Nevertheless, DGSI suffers from the following problems:

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E-mail address: korenson@cs.ccu.edu.tw

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1. Based on FDM, DGSI divides the region of interest (ROI) into grids to approximate the PDEs as a set of linear equations. The approximation is more accurate for smaller grids but at the cost of an increased number of iterations which, in turn, increases communication energy overhead.
2. DGSI coordinates sensors to execute GSI from the ROI's top left to bottom right to compute the solution at each grid point. However, due to the presence of holes (i.e., sensor-less areas in the ROI) or the ROI's irregular shape, some sensors may be unable to collect the information regarding solution precision and thus terminate with fewer iterations, resulting in larger errors.
3. Furthermore, instead of always executing GSI from top left to bottom right of the ROI, the iteration parallelism may be improved by following different iteration orders (e.g., from center the outward).

This paper proposes the distributed Multiplicative Schwarz routing (DMSR) algorithm to alleviate the three DGSI problems of convergence speed, precision, and parallelism. DMSR improves the convergence speed via domain decomposition, i.e., Multiplicative Schwarz method (MSM) [3]. DMSR divides the ROI into subdomains, each of which may contain more than one grid point. Instead of assigning one sensor to compute the solution at each grid point as in DGSI, DMSR assigns one sensor to compute the solution for all grid points in each subdomain. Since there are fewer subdomains than grid points, fewer sensors are required to solve the PDEs and the number of iterations for convergence is reduced, which in turn will reduce the overall communication energy overhead.

Furthermore, DMSR extends the coordination mechanism of the original DGSI to improve the precision and parallelism by adopting customized iteration orders. We then prove the existence of the *atomic iteration order* that can eliminate the aforementioned problem in which some sensors may be unable to collect the information regarding solution precision due to the presence of holes or the ROI's irregular shape. In brief, the contributions of this paper can be summarized as follows:

1. It presents a domain decomposition approach, DMSR, for the load-balancing routing problem in massively-dense WSNs with better convergence speed and less communication energy overhead than the original DGSI.
2. It extends the coordination mechanism of the original DGSI to improve the precision and parallelism by adopting the atomic iteration order.
3. It theoretically proves that the atomic iteration order is optimal in terms of parallelism.
4. It presents a possible remedy with an appropriate atomic iteration order if DMSR does not converge, and theoretically derives the lower bound of the parallelism.

The remainder of this paper is structured as follows. We briefly describe the original DGSI in Section 3 after introducing related work. In Section 4, we illustrate the proposed DMSR algorithm. We first describe the core of DMSR, MSM, and then discuss the requirements for defining an iteration order so DMSR can appropriately coordinate sensors to proceed. We also prove the existence of the atomic iteration order, and present a possible remedy for the failure of DMSR to converge. The simulation results are given in Section 5, and the conclusions are drawn in the final section, together with several suggestions for future research directions.

2. Related work

Greedy forwarding (GF) [4] has been suggested as a promising routing scheme for WSNs because of its simplicity, efficiency, and scalability. In GF, each node uses the line segment from itself to the destination as guidance for selecting the best forwarding node. However, GF faces the local minimum problem in which the presence of holes may cause a node to select itself as the best forwarding node, thus trapping the information packets [5].

Many routing algorithms have been proposed to create various disturbances to allow packets to escape the local minima. For example, a trapped packet may have a chance to escape to a neighbor of the local minima [6] or return to the upstream node for re-forwarding to a different node [7]. In addition, several algorithms use pre-planned bypass paths when packets are trapped. Such bypass paths may be determined using planar subgraphs of the network topology [5,8] or hole boundaries [9–12].

Note that most of the disturbances are based on local environmental conditions, which may result in less than optimal overall performance for the WSN. For example, hole bypassing algorithms that steer packets along the hole boundary may consume excess energy from the boundary nodes which, in turn, may lead to bigger holes. Alleviating this problem requires a global optimization approach to effectively spread the hole bypassing load to non-boundary nodes. However, a globally optimized routing algorithm may suffer from scalability problems.

The scalability problem occurring in massively-dense WSNs may be alleviated via macroscopic analysis [13,14] using techniques developed in branches of physics [15–19], engineering [20,21] and mathematics [22]. For instance, Jacquet [15] and Catanuto et al. [16] analogized a routing path for the propagation of light in geometrical optics, while Chiasserini et al. [17] used a fluid model to analyze the minimum energy consumption routing in which nodes employ a CSMA/CA mechanism to access the channel and may alternate between active and sleep modes. Kalantari and Shayman [18] demonstrated that routing paths spreading traffic uniformly throughout the network can be formulated as a set of PDEs analogous to Maxwell's equations in electrostatic theory. In addition, Jung et al. [19] proposed a potential field-based routing scheme in which the potential field is governed by Poisson's equation via an analogy between physics and a network routing problem.

Altman et al. [20] analyzed globally optimized routing paths via theoretical tools developed for road traffic engineering. They concluded that the non-cooperative case using only paths with minimum costs is a solution of a global optimization problem. The approach used in road traffic engineering was extended to the WSNs with oriented