Journal of Network and Computer Applications 52 (2015) 116–128

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Two-tier particle swarm optimization protocol for clustering and routing in wireless sensor network

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ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form
3 October 2014
Accepted 4 February 2015
Available online 14 March 2015

Keywords:
Clustering
Multi-hop
WSN
PSO
RSSI
CC2420

ABSTRACT

Many cluster-based routing techniques for Wireless Sensor Networks (WSNs) have been proposed in the literature. However, most of the proposed protocols emphasized on the Cluster Head (CH) selection ignoring how the CHs will send the aggregated data back to the Base Station (BS). Furthermore, they tend to use non-realistic parameters and assumptions. Such examples include the use of infinite transmission range and location awareness. They also used an energy model that is fundamentally flawed for modelling radio power consumption in sensor networks. In this paper, two Linear Programming (LP) formulations to the problems of clustering and routing are presented followed by two proposed algorithms for the same based on Particle Swarm Optimization (PSO). The clustering algorithm finds the optimal set of CHs that maximize the energy efficiency, cluster quality and network coverage. The routing algorithm is developed with a novel particle encoding scheme and fitness function to find the optimal routing tree that connects these CHs to the BS. These two algorithms are then combined into a two-tier protocol to provide a complete and practical clustering model. The effect of using a realistic network and energy consumption model in cluster-based communication for WSN will be investigated. Extensive simulations on 50 homogeneous and heterogeneous WSN models are evaluated and compared against well-known cluster-based sensor network protocols. The results demonstrate that the proposed protocol performs better than such protocols in terms of various performance metrics such as scalability, Packet Delivery Rate (PDR) at the CHs and delivery of total data packets to the BS.

1. Introduction

1.1. Background

Wireless Sensor Network (WSN) has emerged as a powerful technological platform with tremendous and novel applications. It has become an important technology in realizing many applications including both simple phenomena monitoring applications and heavy-duty data streaming applications such as military operations, environment monitoring and surveillance systems.

A WSN usually consists of tens to thousands of sensor nodes that communicate through wireless channels for information sharing and cooperative processing (Yu et al., 2006). Usually, the nodes are statically deployed over vast areas. However, they can also be mobile and capable of interacting with the environment.

WSN nodes also can sense the environment, communicate with neighboring nodes, and in many cases perform basic computations on the data being collected (Zungeru et al., 2012; Akkaya and Younis, 2005). These features made WSN an excellent choice for many applications like environmental monitoring, military surveillance, search and rescue, in buildings for infrastructure health monitoring, or even in bodies for patient monitoring (Yu et al., 2006).

There are some factors that affect designing and operating WSN. These factors include energy efficiency and awareness, connection maintenance, minimum resource usage limitation, low latency, network coverage and load balancing in terms of energy used by sensor nodes. Due to these unique inherent characteristics it is a challenging task to select or propose a new routing or communication algorithm for a specific WSN application (Dwivedi and Vyas, 2010).

Using clustering techniques in WSN can help solving some of those concerns, by organizing the network nodes into smaller clusters and elect a cluster head (CH). Sensor nodes in each cluster transmit their data to their respective CH and CH aggregates data and forward them to a central base station (BS) (Abbasi and Younis, 2007). The fact that only the CH is transmitting information out of the cluster helps avoid collisions between the sensors inside the cluster because they do not have to share the communication channel with the nodes in other clusters (Arboleda and Nasser, 2006).

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http://dx.doi.org/10.1016/j.jnca.2015.02.004
1084-8045/

Once the WSN has been divided into clusters, the communication between nodes can be either intra-cluster or inter-cluster. Intra-cluster communication comprises the data exchanges between the member nodes and their respective CH. Inter-cluster communication includes transmission of the data between the CHs or between the CH and the BS.

The process by which data are forwarded efficiently between the CHs and the BS (inter-cluster communication) is an important aspect and essential feature of WSN. A simple method to accomplish this task is for each CH to exchange data directly with the BS (a single hop based approach), or allowing intermediate nodes to participate in forwarding data packets between the CH and the BS (a multihop based approach) (Zungeru et al., 2012). However, in a WSN, individual nodes have limited communication range and form an ad hoc network over a shared wireless medium. Furthermore, the BS is usually located far away from the sensing area and is often not directly reachable to all nodes due to limited communication range and signal propagation problems. A more realistic approach is to use a multihop inter-cluster communication model. For a more reliable data communication, Both data and control packets need to be routed using a multihop communication model (Saleem et al., 2011).

The objective of clustering is to search among a group of sensor nodes to find a set of nodes that can act as cluster-heads. For a given network topology, it is difficult to find the optimal set of CH nodes. For N sensor nodes, there are 2^N-1 different combination of solutions, where in each solution, a sensor node is either elected as CH or non-CH. This has been proved to be a Non-deterministic Polynomial (NP)-hard optimization problem (Agarwal and Procopiuc, 2002).

The basic function of a routing algorithm is to select a route, from the set of available routes, that is most efficient based on some specific criteria. Once the optimal set of CHs is elected in the clustering phase, the next step is to find the optimal routing tree from the CHs to the BS while minimizing the total cost of that tree. Routing is at its most basic level an optimization problem. It also has been known to be NP-hard problem (Dorigo et al., 2006). Therefore, polynomial-time algorithms are impossible to use due to their high computational complexity in real-time communications systems.

Solutions to NP-hard problems involve searches through vast spaces of possible solutions. Swarm intelligence approaches have been applied successfully to a variety of such problems.

Particle swarm optimization (PSO) is a swarm intelligence based optimization method. PSO has many advantages over other alternatives optimization techniques like Genetic Algorithms (GA) which has very high processing demands (Guo and Zhang, 2014). PSO advantages include ease of implementation on hardware or software, high-quality solutions because of its ability to escape from local optima and quick convergence (Kulkarni and Venayagamoorthy, 2011; del Valle et al., 2008). Because of its effectiveness in solving NP problems, PSO has been adopted to optimize the CH election by several centralized clustering protocols. Clustering is a repeated process; therefore, the simpler the optimization algorithm, the better the network efficiency is. This is another reason why PSO is a popular choice for WSN clustering.

1.2. Authors' contributions

In this paper, firstly, we present two Linear Programming (LP) formulations for the clustering and routing problems respectively. Then, two PSO-based protocols for the same problems are proposed.

The PSO-based clustering protocol solves the above CH selection problem by electing CHs in such way that the formed clusters maximize the energy efficiency, network coverage and data transmission reliability of the network.

Then, the PSO-based routing protocol finds the optimal routing tree that connects the elected CHs to the BS. For routing, the particles are cleverly encoded to produce complete routing tree solution. A different fitness function is used to build the trade-off between the energy efficiency and link quality of the constructed tree.

Furthermore, we develop the protocols under realistic network settings. No assumptions were made about the nodes location awareness or transmission range capabilities. The protocols were also tested using a realistic energy consumption model that is based on the characteristics of the Chipcon CC2420 radio transceiver data sheet. Extensive simulations on 90 homogeneous and heterogeneous WSN models are evaluated and compared against 7 existing protocols using several performance metrics including average energy consumption, Packet Delivery Rate (PDR), throughput, network coverage and latency. Our main contributions can be summarized as follows:

- Two LP formulations to the problems of clustering and routing respectively.
- PSO-based clustering protocol with a trade-off between energy efficiency, network coverage and data transmission reliability.
- PSO-based routing protocol with a novel particle encoding scheme for complete routing tree solution and derivation of efficient multi-objective fitness function.
- Investigate the result of using realistic network settings. No assumptions were made about location awareness.
- Investigate the effect of using a realistic energy consumption model in cluster-based communication for WSN.
- Simulation of the proposed protocol to demonstrate its performance against some of the existing protocols in both homogeneous and heterogeneous WSNs.

The remainder of this paper is organized as follows. Section 2 reviews the related work on clustering protocols and the associated drawbacks. Section 3 provides an overview of particle swarm optimization. The system model is presented in Section 4. In Section 5, we present our LP formulations for the clustering and routing problems. Section 6 gives a detailed description of the proposed protocol. In Section 7, we present the experimental results. Finally, Section 8 concludes the work and highlights a few future directions.

2. Related work

Clustering techniques have been studied extensively to improve the performance of WSN (Tyagi and Kumar, 2013; Younis et al., 2006; Abbasi and Younis, 2007). We present the review of such works based on heuristic and metaheuristic approaches.

2.1. Heuristic approaches

Low energy adaptive clustering hierarchy (LEACH) (Heinzelman et al., 2000, 2002) is one of the most popular distributed cluster-based routing algorithms in WSN that has been proven to be an effective approach to prolong the network lifetime. Each node uses a stochastic algorithm at each round to determine whether it will become a CH in this round. Nodes that have been CHs cannot become CHs again for P rounds, where P is the desired percentage of CHs. Therefore, each node has a $1/P$ probability of becoming a CH in each round. The CHs are selected without considering the residual energy or the other properties of the sensor nodes. This random mechanism of selecting the CHs does not guarantee even distribution of clusters over the network (Arboleda and Nasser, 2006).

Hybrid energy-efficient distributed Clustering (HEED) (Younis and Fahmy, 2004) is another distributed clustering protocol that is an extension of LEACH. Cluster formation is achieved with an iterative approach. CHs selection in this protocol is primarily based on the residual energy of each node. To increase energy efficiency and further