Computer Communications 35 (2012) 1392–1409

Contents lists available at SciVerse ScienceDirect

Computer Communications

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

HERO: A hierarchical, efficient and reliable routing protocol for wireless sensor and actor networks

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ARTICLE INFO

Article history:
Received 7 July 2011
Received in revised form 17 February 2012
Accepted 3 April 2012
Available online 13 April 2012

Keywords:
Wireless sensor and actor networks
Reliable routing
Fault-tolerance
Multi-hop
Clustering

ABSTRACT

It is well known that the use of clusters makes wireless sensor and actor networks more scalable, and it also reduces energy consumption and improves their performance. Most hierarchical routing and clustering protocols are designed to be efficient when the data is sent from the sensor nodes to their cluster-head but not when it is sent the opposite way. In this paper, a simple mechanism to form clusters in an efficient way by using meta-data is proposed. And, furthermore, a novelty multi-hop and fault-tolerance routing protocol able to transport data from sensor nodes to their cluster-head and vice versa in an energy-efficient way is also presented. Moreover, this approach allows developers to establish the desired reliability level (in a quantitative way) between two nodes which are *N* hops far away from each other. The performance and the energy consumption of our approach is studied by means of a set of experiments which have been carried out by using the COOJA simulator.

1. Introduction

A new way of distributed computing where hundreds of small devices are able to collaborate in a wireless way is more and more present in our daily life. Sensor nodes, also known as "motes", are able to practically sense and monitor any kind of environment thanks to the fact that any kind of sensor can be attached to these devices. In addition, special devices, called "actors", can take advantage of the collected information in order to act and modify the environment. Both the industry and the scientific community use the term wireless sensor and actor networks (WSANs) to refer to these systems [1].

WSANs allow us to develop a variety of interesting applications which were very difficult to carry out before [2]. Several reports exist that confirm WSANs will be one of the top ten technologies that will have a big impact in the world over the next few years [3].

WSANs are formed by devices with poor resources such as storage, energy, computation, memory, communication and so on. This makes it a great challenge to develop complex WSAN applications on such resource-constrained devices. In addition, depending on the application and the scenario where this application is going to be deployed there will be certain important issues such as collisions, delay, reliability, network overhead, etc., which must be controlled. One of the most used techniques to reduce the impact of these parameters is the organization of nodes in different clusters/groups. It is well known that the use of clusters makes applications more scalable as well as making them more efficient in terms of energy thanks to the communication is reduced to the nodes that belong to the same group (cluster) [4]. However, not everything is advantages as the use of clusters requires the running of a set of algorithms in order to carry out activities such as: cluster formation in a self-organizing way, cluster maintenance, cluster-head election or cluster-head rotation. In WSANs, the cluster-head nodes can act like actor nodes, sinks or both of them. In any case, these kind of nodes are in charge of the maintenance of the group, but in addition, if they are actors, they will use the information received from the sensor nodes to act in consequence. For theses reasons, it is very important to know very well both the scenario that is going to be modeled with the WSAN and the chosen architecture.

Another important topic is the use of routing mechanisms for clusters. Efficient routing protocols are needed in order to transport the data within a cluster in both directions, from the nodes to the cluster-head and vice versa. Normally, within a cluster the most frequent communication is carried out from the nodes to the cluster-head. The communication from the cluster-head to the nodes is less frequent but no less important. Two of the main reasons of why this communication is needed are: (1) Nodes raise critical events which may need to be confirmed by the cluster-head with a ACK packet, and (2) To support a query-driven model. A large number of papers about routing have been presented, but a lot of them are only based on event-driven models, others assume the cluster-head can directly communicate with the nodes (one hop), others assume the communication is one hop in both

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http://dx.doi.org/10.1016/j.comcom.2012.04.003

directions and to the best of our knowledge, there is only one approach [5] which allows developers to define the reliability level of a quantitative way (for example, reliability level about 84%).

In this paper, we present a novel approach to address the issues such as cluster formation and reliable multi-hop routing based on clusters in an efficient way without having to use a lot of resources. On the one hand, the protocol used to form the clusters does not use costly mechanisms like flooding. In addition, the protocol is not centralized in the cluster-head, but the nodes are in charge of joining in the clusters through its neighbors. It allows any node situated in the cluster region to be able to join in the cluster in a proactive way, that means, the nodes do not have to wait for the cluster-head to execute a discovery protocol in order to find possible nodes. On the other hand, the multi-hop routing protocol is thought to address both event-driven and query-driven data models. For sensor nodes to cluster-head communication, the protocol is thought to transport data through the shortest path trying to balance the energy consumption. On the other hand, to address cluster-head to sensor nodes communication we introduce the concept of "clue node" through which a cluster-head will be able to estimate the area where the nodes with which it wants to communicate are located. For the cluster-head it is much more feasible to approximately know where the nodes are than to exactly know where they are.

We would like to emphasize the fact that our work is a contribution to the WSAN research field in the sense that it effectively provides the following innovations:

- Cluster formation is carried out without using energy-inefficient protocols like flooding or multicast thanks to meta-data stored in the nodes before they are deployed. It allows nodes to communicate with their neighbors only when it is necessary, and as consequence, nodes save a considerable amount of energy.
- Most papers published so far only have as the main goal achieving an efficient communication when the packets are sent from the sensor nodes to their cluster-head. We also provide an efficient mechanism to carry out this kind of communication, but we also consider important the communication carried out from the cluster-head to the sensor nodes. To make this kind of communication more efficient we propose two concepts: "memory-path" and "clue-node". The former is used when a cluster-head has to answer an event received from a sensor node. It stores the last four nodes used to reach the cluster-head in order to use them for transmitting the answer. The latter is used by the cluster-head when it wants to communicate with a particular sensor node. "Clue-node" helps the cluster-head to estimate the zone where the packets have to be sent.
- Developers will be able to specify the desired level of reliability between sensor nodes and their cluster heads, and viceversa in a quantitative way. That is, they will have the possibility of indicating that the temperature and smoke events have to be delivered in the cluster-head with a probability of 80% and 95% respectively. And, for example, they can also specify a reliability of 98% in commands in charge of checking the health of a specific node.
- As overall contribution, the approach presents a powerful, efficient and robustness protocol which can be easily integrated with the WSAN applications to carry all the communication process.

The rest of the paper is structured as follows. Section 2 summarizes the related work. Section 3 presents the proposed protocol called HERO. Sections 4 and 5 discusses the performance evaluation of the proposed protocol and compare it with two routing protocols in terms of energy efficiency. Finally, Section 6 concludes the paper.

2. Related work

Owing to the fact that both clustering and routing are two really important issues in the WSANs field, a large number of papers have been published trying to address them. The offered solutions are very varied and the problems are approached from different point of views. GBR [6] presents one of the first gradient-based routing protocols which is based on the directed diffusion paradigm [7]. This approach uses techniques like SPIN [8] to flood into the network the information in which nodes are interested so that gradients are established in each node. This allows the nodes to discover the minimum number of hops to the sink. In contrast, although our approach also uses the gradient technique, mechanisms like flooding are not needed by the nodes to know their gradients to the sink. In [9] the authors propose a model where the nodes communicate with the sink by using multi-hop whereas the sink is able to communicate with them by using single-hop communication. They also assume that nodes are connected by directional wireless links with a cost associated with each direction. This information is used to discover the more energy-efficient path, but is not explained how this information is obtained. In our work no type of assumption is established. Both nodes and sink within a same cluster can communicate in a bidirectional way by using multi-hop.

Almost all routing protocols can be classified as flat, data-centric, hierarchical and location-based protocols. Maybe the most proper kind of approach to organize and establish communication between the nodes of a WSAN is that based on hierarchical protocols [10]. In the following, a brief comparison between our hierarchical approach and those already in existence is commented on. LEACH [11] is one of the most popular hierarchical routing algorithms for sensor networks. It is a completely distributed clustering-approach and requires no global knowledge of the network. However, it uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Furthermore, the idea of dynamic clustering brings extra overheads, which may diminish the gain in energy consumption. In contrast, our approach not only permits multi-hop communication in both directions, but it is also able to create clusters in an energy-efficient way and without extra overheads. BCDCP [12] is an approach which address the routing issue by means of clusters. This approach operates in two major phases: setup and data communication. Despite this approach is more energy-efficient at creating clusters than other proposes such as LEACH [11], LEACH-C [13] or PEGASIS [14], the mechanisms needed in order to create clusters, to choose their cluster-head and to maintain the cluster information suppose an overhead. Regarding the data communication phase, the algorithm is focused on how to transport the data from a cluster-head to the sink through the different cluster-heads. But, mechanisms to transport the data from the nodes to the cluster-head and vice versa are not explained. Recently [15] have proposed a clustering algorithm based mainly on the node position with respect to the actor nodes and the remaining energy of the nodes. The algorithm distinguishes between three kinds of nodes: member nodes, cluster-head and actor nodes, so that, member nodes send the sensed information to their cluster-heads, and then send this information to the actor nodes. In contrast, HERO is not restricted to only three different tiers, but it allows developers to specify as many tiers as they want (one, two, three, ...). In addition, in HERO, nodes do not need to know the exact position of where they are. Other different approach is MuMHR [16]. This approach uses two phases, the set-up phase and the data transmission phase. One the one hand, the communication overhead in the set-up phase is reduced by using back-off time [17] for the advertisement messages. On the other hand, it adds reliability to the protocol and nodes transmit over multiple path transmissions by using multi-hop. Furthermore,