Computer Communications 81 (2016) 61–71

Contents lists available at ScienceDirect

Computer Communications

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

Cooperative interaction among multiple RPL instances in wireless sensor networks

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ARTICLE INFO

Article history:
Received 21 January 2015
Revised 24 December 2015
Accepted 26 December 2015
Available online 31 December 2015

Keywords:
Wireless Sensor Networks
Routing
RPL
Multiple instances
Heterogeneous traffic

ABSTRACT

Advanced Wireless Sensor Networks (WSNs) applications may need to develop multiple tasks that involve sensing, processing and gathering data from different sensing units. This heterogeneous data may have multiple and sometimes opposite sets of requirements. In these scenarios, different networking strategies must be combined, and therefore traditional single-tree routing approaches are not efficient. On the contrary, the well-known RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) protocol virtually splits the network into multiple RPL Instances, that transport each kind of data according to its particular objective function. However, this protocol does not define any mechanism to decide the nodes that must belong to each instance, and this decision has a strong impact in the network energy consumption and performance. With this in mind, in this paper we introduce C-RPL (Cooperative-RPL). This creates multiple instances following a cooperative strategy among nodes with different sensing tasks. As a result, the energy consumption, the complexity and the cost of the nodes is reduced compared to RPL, since they are active less time, perform fewer tasks and are equipped with less sensing hardware. In this paper we also propose a novel fairness analysis for networks with multiple instances, showing that C-RPL achieves a better tradeoff, in terms of performance and energy consumption, than RPL with non-cooperative instances.

1. Introduction

Wireless Sensor Networks (WSNs) are a set of autonomous, battery powered nodes connected by wireless links that gather information about the environment. These networks are being used in many scenarios thanks to its reduced cost. However, in many of these scenarios, such as a forest or a battlefield, the replacement of their batteries can be difficult or even impossible. Then, it is necessary to minimize their energy consumption in order to extend their lifetime and keep them operative as much as possible. It is well-known that the main source of energy consumption in WSNs is the radio transceiver. Therefore, practical energy efficient communication schemes are required in order to extend their lifetime in real-life scenarios.

Many advanced WSN applications need to develop multiple tasks. For instance, SHM (Structure Health Monitoring) [1] systems need to collect information coming from different sensing units, such as pressure, vibration or temperature. Moreover, they also need to send alarm messages in case of broken sections or systems failures. In addition, continuous messages are broadcast for external monitoring and calibration. All this heterogeneous traffic needs to be properly managed by the network [2]. For instance, latency is a critical requirement in event detection applications [3]. A minimum hop strategy is frequently adopted in these applications, since packets need to be decoded, processed and coded again in each hop. On the contrary, critical monitoring tasks may admit a certain delay in some cases, but they require a high reliability [4]. The performance of these applications strongly depends on the packet delivery ratio at the destination, and therefore only the most reliable links should be considered. On the other hand, ambient monitoring applications may not have strict delay or reliability constraints, but a low energy consumption becomes crucial because periodic packet transmissions are generally required [5].

The well-known RPL (Routing Protocol for Low-Power and Lossy Networks) protocol [6] is a reliable and efficient routing protocol that can be easily configured with personalized objective functions. Moreover, multiple objective functions can be considered in the same WSN by virtually splitting the network into multiple RPL Instances, which group nodes with common traffic requirements. Then, each instance can be individually configured to address the QoS (Quality of Service) requirements of a specific kind of traffic.

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http://dx.doi.org/10.1016/j.comcom.2015.12.008

Unfortunately, RPL does not define any mechanism to create RPL Instances according to the node distribution and network conditions, and hence they must be defined manually in advance. In order to divide the network in RPL Instances, the network designer could either adopt a low-consumption strategy (i.e. each node belongs only to the instance associated to its tasks) or a high-reliability strategy (i.e. any node may belong to any instance as long as it senses or forwards the kind of traffic associated to that instance). On one hand, the first strategy may reduce the network performance, due to the reduction of the node density of each instance. On the other hand, the second strategy does not consider that nodes associated to different tasks may have different duty cycles. As a result, this solution may not be energy efficient, since it does not prioritize the communication among nodes with the same duty cycle. Then, many nodes may have to extend their active time, and thus increasing their energy consumption.

In this paper, we propose a cooperative RPL-based strategy (C-RPL) to manage this tradeoff. This defines the nodes that belong to each RPL Instance, referred in C-RPL to as C-RPL Instances, following a cooperative strategy among instances. Taking into account the selfish nature of nodes, the coalitions among the instances are created according to a utility function that considers the tradeoff between the performance and the energy consumption associated to each coalition. From a game theoretical perspective, the solution of the cooperation problem among RPL Instances, such as the solution of the WSN cooperation problem in [7], is very similar to the well-known prisoner's dilemma game [8]. Briefly, this is a two person zero game that describes a situation where two players increase their utility if they both cooperate, but if a player decides not to cooperate while the other cooperates, its utility gain is even higher than cooperating. Therefore, players will never cooperate (i.e. Nash equilibrium of the prisoner's dilemma game). This game is suitable for studying complex interactions among players, such as the cooperation among RPL instances, since rational actions do not cause the Pareto optimality. In C-RPL, we avoid that instances do not collaborate using the sink node as a supervising entity.

On the other hand, since multiple performance criteria may be involved, it is important to distribute the network resources in a "fair" manner (i.e. considering the different requirements of all the traffics in the network). Although many definitions can be found in the literature to evaluate fairness [9], such as weighted fairness, max-min fairness or proportional fairness, to the best of the authors knowledge, not any of these definitions has been used before when different objective functions are considered in the same network. In this paper, we propose a metric to evaluate the overall network fairness in networks with multiple instances, which may have different objective functions.

The main contributions of this paper are as follows:

- We address the performance and energy efficiency issues that may appear in RPL in the presence of heterogeneous traffic. Then, we propose a novel approach (C-RPL) that coordinates the RPL Instances to form energy efficient coalitions according to their individual objective functions and the network conditions.
- We propose a mechanism to evaluate fairness in networks with multiple RPL Instances. This evaluates the distribution of the existent network resources to address the different, and sometimes contradictory, objective function of each instance.

The rest of the paper is organized as follows: Section 2 introduces previous work related to the management of heterogeneous traffic in WSNs. Section 3 describes the principles of the RPL protocol. Section 4 introduces C-RPL, explaining how instances evaluate the potential coalitions, and also the cooperation game among these instances. Section 5 proposes a metric to evaluate fairness in networks with multiple instances. Section 6 presents and analyzes the simulation results. Finally, Section 7 summarizes the paper and presents the main conclusions.

2. Related work

Multi-objective routing approaches, such as [10,11], consider multiple criteria simultaneously to handle different QoS requirements. These strategies find a tradeoff solution taking into account multiple objective functions at the same time. For instance, in [12] the authors propose a solution to increase the lifetime and throughput of the network, while reducing its latency. In [13], the aggregate energy consumption and delay are optimized using genetic algorithms. However, the requirements of different kinds of traffic may not be satisfied with multi-objective routing, since they are not addressed individually. Note that frequently, these requirements have contradictory relationships among them [14].

The QoS requirements of multiple kinds of traffic can be individually addressed through buffering or prioritized Medium Access Control (MAC) mechanisms [15]. At the network layer, it is also possible to provide QoS differentiation through multiple routing trees. Although this mechanism has been mainly used in the literature for load balancing [16] or to increase the network robustness in front of faulty links [17], it can also be used to efficiently manage the QoS requirements of heterogeneous traffic [18]. In fact, RPL divides the network in multiple trees, referred to as RPL Instances, to enable the network to manage traffics with different requirements. In [19], two RPL instances are defined to individually manage latency constrained and high priority traffic in Smart Grids. In particular, they construct each RPL Instance according to the minimum number of hops and the minimum expected number of transmissions (ETX), respectively. In [20], the authors differentiate between nodes for monitoring purposes, and nodes for high priority traffic (alarms). In order to manage these traffics, they create one instance that is only composed of nodes from the first group, and also a second instance that groups nodes from both groups. However, any of these strategies define how to dynamically select the nodes that belong to each instance, and therefore this decision must be taken in advance. Note that the best solution may strongly depend on the current network conditions.

3. Principles of RPL

Gradient-based routing is an energy efficient and reliable solution to construct convergecast trees. This technique uses control messages (also referred to as pilots or beacons) to evaluate the quality of the wireless links. The link quality estimator metric can be based on different criteria, such as reliability, number of hops, node battery level, energy consumption, and so on. The particular metric should be selected according to the application requirements. GBR (Gradient-Based Routing) is the classical gradient routing protocol, but there also exist other gradient-based implementations, such as CTP (Collection Tree Protocol) [21], RPL [6], and the hierarchical routing defined in ZigBee [22].

In this paper, we consider RPL, since it is specially designed for Low-Power Lossy Wireless Networks (LLNs), such as WSNs. This has been standardized by the IETF ROLL working group. RPL constructs convergecast trees, referred in RPL to as DODAGs (Destination Oriented Acyclic Graphs), rooted at the sink node. In the presence of multiple kinds of traffic, RPL may create multiple instances to serve different and potentially antagonistic objective functions [19]. Each RPL Instance uses a unique objective function, but it may include one or multiple DODAGs constructed with this objective function. For the sake of simplicity, in this paper we assume that each RPL Instance includes only one DODAG. According to the particular objective function of each DODAG, the nodes compute their relative distance to the sink, referred