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Cross-layer network formation for energy-efficient IEEE 802.15.4/ZigBee Wireless Sensor Networks

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ABSTRACT

In IEEE 802.15.4/ZigBee Wireless Sensor Networks (WSNs) a specific node (called the PAN coordinator or sink) controls the whole network. When the network operates in a multi-hop fashion, the position of the PAN coordinator has a significant impact on the performance: it strongly affects network energy consumption for both topology formation and data routing. The development of efficient self-managing, self-configuring and self-regulating protocols for the election of the node that coordinates and manages the IEEE 802.15.4/ZigBee WSN is still an open research issue. In this paper we present a cross-layer approach to address the problem of PAN coordinator election on topologies formed in accordance with the IEEE 802.15.4. Our solution combines the network formation procedure defined at the MAC layer by the IEEE 802.15.4 standard with a topology reconfiguration algorithm operating at the network layer. We propose a standard-compliant procedure (named PAN coordinator ELection – *PANEL*) to self-configure a IEEE 802.15.4/ZigBee WSN by electing, in a distributed way, a suitable PAN coordinator. A protocol implementing this solution in IEEE 802.15.4 is also provided. Performance results show that our cross-layer approach minimizes the average number of hops between the nodes of the network and the PAN coordinator allowing to reduce the data transfer delay and determining significant energy savings compared with the performance of the IEEE 802.15.4 standard.

1. Introduction and motivation

Wireless Sensor Networks (WSNs) are traditionally composed of multiple sensor nodes that sense environmental phenomena, such as atmospheric pressure, temperature, sound, vibration, etc., and generate sensor readings that are delivered, typically, through multi-hop paths, to a specific node (called the sink) for collection [1,2]. In a WSN, the position of the nodes can be predefined, thus satisfying optimal coverage and connectivity constraints. As an example, the authors in [3] study an algorithm for optimal node positioning in order to minimize the required number of nodes, yet guaranteeing perfect sensing coverage of the monitored field. However, in several contexts, the position of the nodes cannot be predefined. When WSNs are used for pervasive data collection in urban areas or to provide real-time monitoring in emergency scenarios, sensors may be randomly scattered and possibly re-deployed over time in the considered area. Work that address energy-efficient network topology formation for such scenarios has been proposed, e.g., [4]. However, the formation of network topologies that are energy-efficient and meet quality of service requirements is still an open problem [5]. The development of self-managing, self-configuring and self-regulating network and communication infrastructures is gaining considerable interest, both in the research and industrial communities [6]. The need to identify optimal topology formation and efficient PAN election for urban sensing or disaster recovery applications opens up novel research opportunities. The IEEE 802.15.4 Personal Area Network (PAN) standard [7] addresses the formation and management of low energy and low cost WSNs. It defines the physical and MAC (Medium Access

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Control) layers, while the upper layers of the protocol stack (network and applications) are specified by the ZigBee Alliance guidelines [8]. Recently, some papers have presented an analysis of the IEEE 802.15.4 standard discussing its capabilities, application scenarios, and performance [9–11]. The paper in [10] presents an overview of the energy efficiency, communication, data management and security solutions that can be adopted for this standard. Other work has been proposed to address several networking issues present in the IEEE 802.15.4/ZigBee, such as efficient data broadcasting [12], coexistence of multiple co-located networks under different interference conditions [13], and device localization [14].

In our previous work we show that the position of the PAN coordinator strongly affects the network energy consumption for both network formation and data routing [5,15]. In this article we present a novel, resource aware and energy efficient algorithm for PAN coordinator election in IEEE 802.15.4/ZigBee WSNs. Adopting a cross-layer approach, the proposed algorithm operates at the network layer of a WSN that relies on the IEEE 802.15.4 MAC layer for the network formation, as represented in Fig. 1. The topology of a WSN formed according to the IEEE 802.15.4 MAC layer is a *cluster-tree* where the PAN coordinator is at the root of this tree. Our proposed algorithm (named PAN coordinator ELection-*PANEL*) operates at the network layer to reconfigure the network topology in order to achieve optimal PAN coordinator placement, improve energy savings, and reduce routing delay.

Briefly, PANEL works as follows: as the cluster-tree topology is formed, PANEL assigns the role of PAN coordinator to a different node in the tree. To do so, PANEL adopts a distributed approach with the result of determining a new tree topology for the network where the maximum and the average number of hops to the PAN coordinator are minimized. In this way, PANEL is able to reduce the energy cost of the network and improve its performance by, respectively:

- minimizing the number of hops between the source of the sensor readings and the sink;
- reducing the packet drop rate due to fewer packet collisions at the MAC layer.

Results from our experimental evaluation show that PANEL successfully prolongs WSN lifetime and achieves optimal PAN coordinator election.

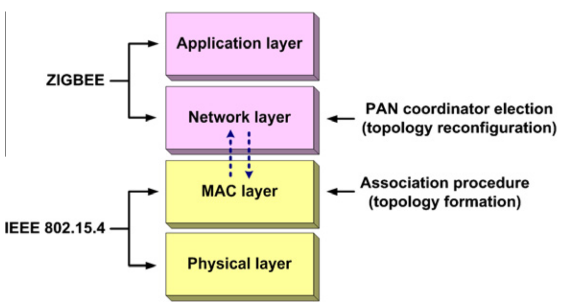

Fig. 1. Cross-layer approach for PAN coordinator election in IEEE 802.15.4/ZigBee WSNs.

PANEL can be easily integrated on top of the IEEE 802.15.4/ZigBee stack and it is fully compliant since it relies on data structures and transmission packets defined in the IEEE 802.15.4 standard, such as the beacon packets. By exploiting the beacons, PANEL is able to: (1) obtain information about the cluster-tree topology formed by the IEEE 802.15.4 MAC layer; (2) leverage the beacon packet fields to enclose topological information that are needed to optimally reconfigure the network topology.

The paper is structured as follows. Section 2 describes the IEEE 802.15.4 topology formation mechanism. In Section 3 the impact of the PAN coordinator position on the network energy consumption is discussed. The PANEL algorithm is presented in Section 4. Section 5 shows an extensive performance evaluation of PANEL and a comparison with the basic IEEE 802.15.4. A discussion on the related work is reported in Section 6, while concluding remarks can be found in Section 7.

2. The IEEE 802.15.4 network formation procedure

A IEEE 802.15.4 WSN is composed of one PAN coordinator (denoted in the following as p) and a set of nodes [7]. The network topology defined in the standard is called cluster-tree, where nodes associated with p establish parent–child relationships and form a tree rooted at p. Two node typologies can be identified in a IEEE 802.15.4 network: Full Function Devices (FFD), which are allowed to associate with other nodes in the network, and Reduced Function Devices (RFD), which are not allowed to associate with other nodes. The PAN coordinator and the intermediate nodes, that perform data relay, belong to the FFD class, whereas the nodes that are leaves in the cluster-tree are part of the RFD category.

The PAN coordinator is the controller of the network and it is responsible for initiating the network set-up. All nodes relaying data traffic can be also considered coordinators and we name them c to distinguish them from the PAN coordinator p. We can then identify two logical and hierarchical layers in the network (refer to Fig. 2): the FFD and RFD layer. PANEL operates only at the FFD layer, i.e., only on nodes acting as coordinators.

The standard defines the steps taken by p and the other nodes to initialize and form the network, respectively. Node p starts by selecting a suitable communication channel. This selection is performed by the energy detection scan which assesses the level of interference on each channel by measuring the peak energy on each available channel (16 channels in the 2.4 GHz ISM band). Nodes join the network according to the *association procedure*, where each node performs the following operation: (1) it searches for

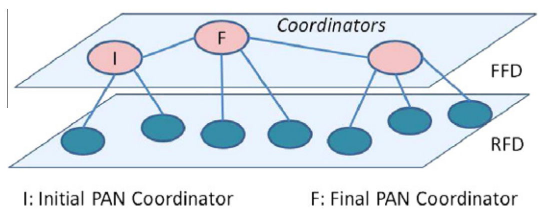

Fig. 2. Example of a WSN scenario with FFDs and RFDs.