A Distributed Procedure for IEEE 802.15.4 PAN Coordinator Election in Emergency Scenarios

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1 Introduction

Communication networks play a fundamental role in the response to massive catastrophes, such as earthquakes, floods, fires, and so on. When one of these events happens in an urban area, public authorities are expected to undertake all actions that are necessary to control and to limit damages for people and for buildings. A central authority, usually, takes the role of coordinating all operations in the emergency scenario and, to this aim, it needs to know in real-time the exact situation in the place where the disaster has happened and to communicate with all the teams deployed within the catastrophe area.

In such a scenario, the presence of a reliable communication infrastructure is fundamental, in order to allow communications, especially among emergency agents (like policemen, firemen, doctors, etc.) and to send and to receive information to/from a remote center, responsible for the emergency management. This communication infrastructure will be composed by a set of different network technologies, devoted on one side to the transmission, also at long distances, of information (e.g., third generation cellular networks or WiMax networks) and, on the other side, to the collection of data within the disaster area and to the communication, in the same area, among emergency agents [e.g., wireless personal area networks (WPANs)].

In this chapter, we focus on network technologies that allow, in an emergency scenario, the communication among people and the collection of specific data of interest (like temperature and humidity degree in the event of fire). Such technologies should be able to self-configure quickly and to guarantee a lifetime sufficient for an efficient emergency management. An IEEE 802.15.4 WPAN is a good candidate to take this role, thanks to its pervasive nature [1]. In this network, a specific node (called *PAN coordinator*) takes the control of the network and its position has a significant impact on the performance [2–4].

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We present a study on the self-configuration of IEEE 802.15.4 WPANs in emergency scenarios, with specific attention to procedures of election of the PAN coordinator. As stated in [5], the development of self-managing, self-configuring and self-regulating networks, and communication infrastructures is an area of considerable research and industrial interest. In an application context, as the one relevant to the management of catastrophes, the use of autonomic and self-configuring techniques for controlling the selection of the PAN coordinator opens new prospectives.

We propose a distributed procedure, that works in an autonomic way, to elect the best node to perform the PAN coordination. This heuristic procedure aims at moving, whatever node starts the network formation in accordance to the standard IEEE 802.15.4, the PAN coordinator role to a target position which guarantees the minimum *network depth* (its meaning is explained in Sect. 2). Specific consequences of selecting the PAN coordinator in accordance to our procedure are energy saving during data delivery, thus increasing the network lifetime in case of battery supplied devices [e.g., in case of wireless sensor networks (WSNs)] and delivery delay reduction. On the contrary, if any other node is selected as PAN coordinator, network performance worsen. In self-configuring networks, our distributed procedure can be used after the network has just formed to reorganize the topology selecting in a suitable way a new PAN coordinator.

The chapter is structured as follows: Sect. 2 recalls the main characteristics of the IEEE 802.15.4 topology formation. In Sect. 3, we describe the reference architecture scenario. In Sect. 4, we present our distributed procedure for PAN coordinator election and we evaluate it in Sect. 5. Finally, the overall conclusions of the paper are provided in Sect. 6.

2 Self-Configuration of an IEEE 802.15.4 WPAN

An IEEE 802.15.4 WPAN is composed of one PAN coordinator and a set of nodes [6]. A typical network topology defined in the standard is the so-called cluster tree, where nodes associated to a single PAN coordinator are arranged in a tree with parent–child relationships. In an IEEE 802.15.4 network, it is possible to have Full Function Devices (FFDs) that allow the association of other nodes to the network, and Reduced Function Devices (RFDs) that do not permit the association of other nodes. The PAN coordinator is always a FFD, intermediate nodes allowing data relay (router) are FFDs too, whereas RFDs are leaves of the tree.

The standard defines a set of procedures implemented by the PAN coordinator to initiate a new WPAN and by other nodes to join an existing WPAN. The PAN coordinator starts by selecting a suitable channel. This selection is performed by the Energy Detection (ED) scan which measures the interference (i.e., the *peak energy*) of each available channel (16 channels in the 2.4 GHz ISM band). The procedure adopted by nodes to join a WPAN is named *association procedure* and it establishes relationships between nodes within a WPAN. The operations performed by a node to join a WPAN are (1) the node searches for the available WPANs, (2) it selects a coordinator[1] belonging to the available WPANs and (3) it starts a message exchange with the selected coordinator to associate with it.

The discovery of available WPANs is performed by scanning the *beacon frames* broadcasted by the coordinators.

The level l of a node in the tree is intended as the distance (in terms of number of hops) of the node from the PAN coordinator. We define *network depth* (or *tree depth*) L as the maximum distance of a node from the PAN coordinator within the tree, i.e., the maximum value of l. We indicate with L_i the tree depth when the node i is the PAN coordinator. The variable g is instead the mean level of a node in the tree (g_i is the mean level of a node in the tree when node i is the PAN coordinator). These values are affected by the position of the PAN coordinator.

3 Considered Network Architecture for Emergency Scenarios

As explained in Sect. 1, the management of an emergency event requires the use of a communication infrastructure in the disaster area. In this context, thanks to the pervasive nature of their devices, the use of IEEE 802.15.4 WPANs seems particularly appropriate for the following reasons:

1. Emergency agents (like policemen, firemen, doctors, etc.) require a communication infrastructure able to self-configure in a fast manner and to guarantee a lifetime sufficient for an efficient emergency management.
2. In the emergency area, the collection of specific data of interest (like temperature, humidity, movements, etc.) could be very important for the emergency management.

In Fig. 1, an example of the use of IEEE 802.15.4 WPANs in an emergency area is reported. IEEE 802.15.4 FFDs and RFDs can be interconnected to form several WSNs. Each of them has a limited coverage area (e.g., some dozen of meters) and it is responsible for data collection in the area where it is deployed. Other IEEE 802.15.4 FFDs, instead, are interconnected to form one or more WPANs. These networks have a coverage area greater than WSNs, and they allow communications among emergency agents. Moreover, they are responsible for the collection of data revealed by WSNs and, for this reason, some nodes of WPANs have to be connected with RFDs. Each WPAN has its own PAN coordinator, instead a WSN can have or not its own PAN coordinator. In the latter case, the role of PAN coordinator of the WSN is taken by an FFD of the WPAN directly connected to the same WSN.

With reference to Fig. 1, the procedure for PAN coordinator election that we propose in this paper has an impact on both WPANs and WSNs (in terms of network

[1] Coordinators are all nodes that can act as relay nodes.

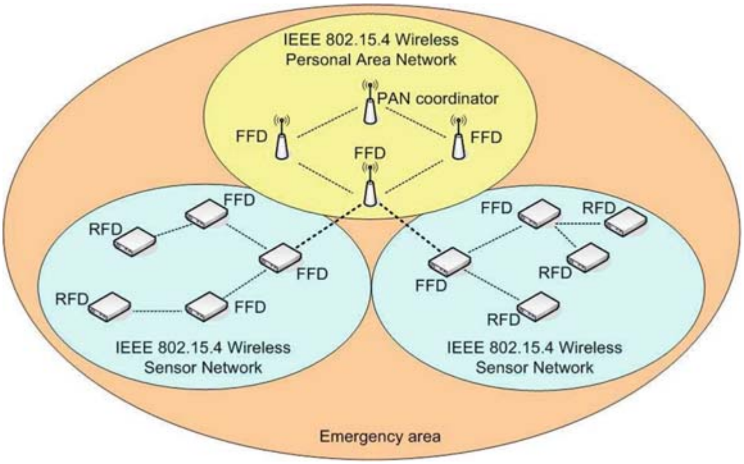


Fig. 1 A possible (pervasive) use of IEEE 802.15.4 WPANs in an emergency area

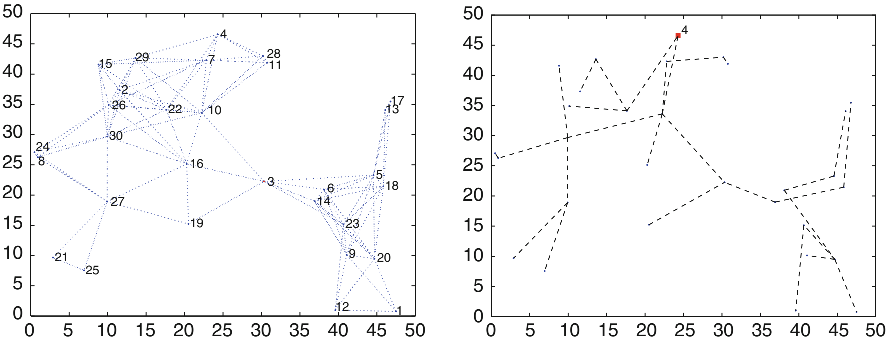
topology and performance). The selection of the node having the role of PAN coordinator affects the following topological characteristics:

- The structure of the parent–child relationships
- The number of nodes at different levels of the tree
- The tree depth

The optimization performed in the cluster-tree topology, reflects to the routing delay and energy consumption when a hierarchical routing protocol (see paper [7]) is applied. In this case, data generated by nodes and directed to the PAN coordinator are routed upward to the root tree along the parent–child relationships, i.e., every node relays data to its parent. Therefore, the energy consumption and the delivery delay due to data transmission are proportional to the number of hops of the path from the source node to the destination node (i.e., PAN coordinator).

4 A Distributed Procedure for PAN Coordinator Election

We propose a distributed procedure (named PANEL – PAN coordinator ELection) aiming at moving the PAN coordinator role to a node that has a specific position in the formed network. We consider N nodes, having transmission range R, randomly deployed in a given area (as in the example of Fig. 2a). A generic node starts the WPAN in accordance to the IEEE 802.15.4 standard and form a network. The starting point is then a network topology formed by means of the IEEE 802.15.4 association procedure. In Fig. 2b, the network resulting from a formation started by node 4 is shown. This network topology is a tree having as root node a PAN coordinator p^{IN}, that initially is in general nonoptimal, and presenting a tree depth L_{IN}. PANEL is iterative algorithm. The idea behind PANEL is the following: in order to



(a) Nodes and nodes' visibilities.

(b) Network formed by running the IEEE 802.15.4, node 4 is the PAN coordinator.

Fig. 2 An example of network including 30 nodes. The numbers represent nodes' identifiers

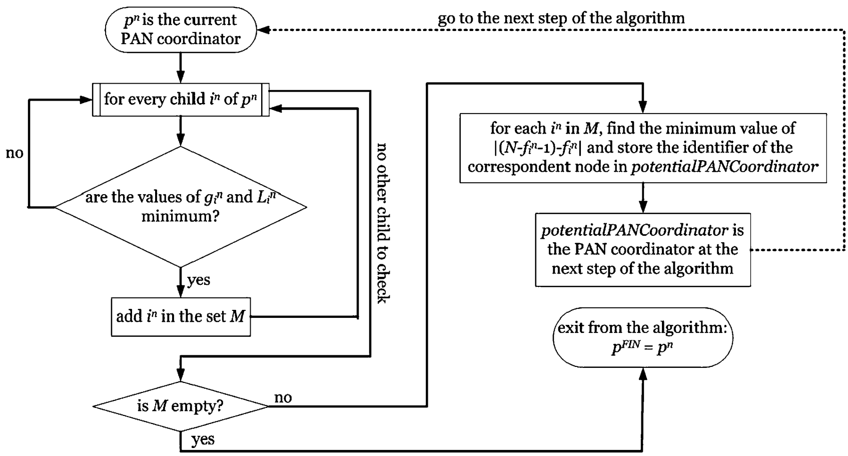


Fig. 3 Simplified flow chart describing PANEL

improve performance of the topology resulting from the IEEE 802.15.4 (in terms of energy consumption and data delivery delay), the node that should be elected as PAN coordinator is the one that allows:

1. To decrease the mean level of nodes within the tree
2. To decrease the tree depth
3. To guarantee the best *network balancing*, among all nodes that satisfy the previous two conditions

We point out that PANEL results in the best choice of the PAN coordinator given a specific starting topology and, thus, the output of the procedure depends on the topology given as input.

The n-th iteration of PANEL implements the steps of the flow chart in Fig. 3. Let p^n be the PAN coordinator at the beginning of iteration n. Every child i^n of

p^n ($i^n = k_{1^n}, k_{2^n}, ..., k_{m^n}$, where m^n is the number of children of p^n) sends to it three data: the mean level of a node in the tree g_{i^n} and the tree depth L_{i^n} if i^n was elected PAN coordinator, and the number of its descendants f_{i^n}, that is the number of nodes of the subtree having it as root. Nodes get this information from data structures (i.e., *vectors*) built during the association procedure. In fact, by exploiting messages exchanged in this phase, every node i^n computes a vector V_{i^n} whose jth element $V_{i^n}[j]$ indicates the number of nodes that are j hops away from the node i^n in the subtree having i^n as root. Let V_{p^n} the vector of p^n (the PAN coordinator at the beginning of iteration n) and V_{i^n} the vector of the generic child i^n of p^n; p^n sends V_{p^n} to all its children, so the generic child i^n computes the operations described in Pseudo-code 1, in order to calculate g_{i^n}, L_{i^n} and f_{i^n}.

Pseudo-code 1 COMPUTATION OF g_{i^n}, L_{i^n} AND f_{i^n}

1: $V^*_{i^n} = V_{i^n}$;
2: add in queue to $V^*_{i^n}$ a number of *zero* elements equal to: *size* (V_{p^n}) - *size* (V_{i^n}) + *1*;
3: $V^{**}_{i^n} = V^*_{i^n}$;
4: shift right one position the elements of $V^{**}_{i^n}$;
5: add in queue to V_{p^n} one element equal to 0;
6: $V^{**}_{i^n} = V_{p^n} - V^{**}_{i^n}$;
7: $V^{**}_{i^n}[1] = V^{**}_{i^n}[1] - 1$;
8: shift right one position the elements of $V^{**}_{i^n}$;
9: $V^{**}_{i^n}[1] = V^{**}_{i^n}[1] + 1$;
10: $V^{**}_{i^n} = V^{**}_{i^n} + V^*_{i^n}$;
11: $g_{i^n} = 0$;
12: $sumElements = 0$;
13: **for** $j = 1, 2, ..., size(V^{**}_{i^n})$ **do**
14: $\quad g_{i^n} = g_{i^n} + j \cdot V^{**}_{i^n}[j]$;
15: $\quad sumElements = sumElements + V^{**}_{i^n}[j]$;
16: **end for**
17: $g_{i^n} = g_{i^n}/sumElements$;
18: remove from $V^{**}_{i^n}$ potential zero element in queue;
19: $L_{i^n} = size(V^{**}_{i^n})$;
20: $f_{i^n} = 0$;
21: **for** $k = 1, 2, ..., size(V_{i^n})$ **do**
22: $\quad f_{i^n} = f_{i^n} + V_{i^n}[k]$;
23: **end for**

The vector $V^{**}_{i^n}$ as obtained at line 10 of Pseudo-code 1 indicates the number of nodes at different levels of the tree if i^n was elected PAN coordinator. In Fig. 4, it is shown as an example of computation of this vector made by the generic child i^n of a PAN coordinator p^n. After this computation, the node i^n calculates g_{i^n}, L_{i^n} and f_{i^n}, in accordance with the steps from line 11 to line 23 of Pseudo-code 1. In case of Fig. 4, at the end of Pseudo-code 1, i^n will obtain: $g_{i^n} = 1.778$, $L_{i^n} = 3$ and $f_{i^n} = 5$. We point out that the computational and storage resources requested to nodes are very low and thus in step with the constrained capacities of IEEE 802.15.4 nodes.

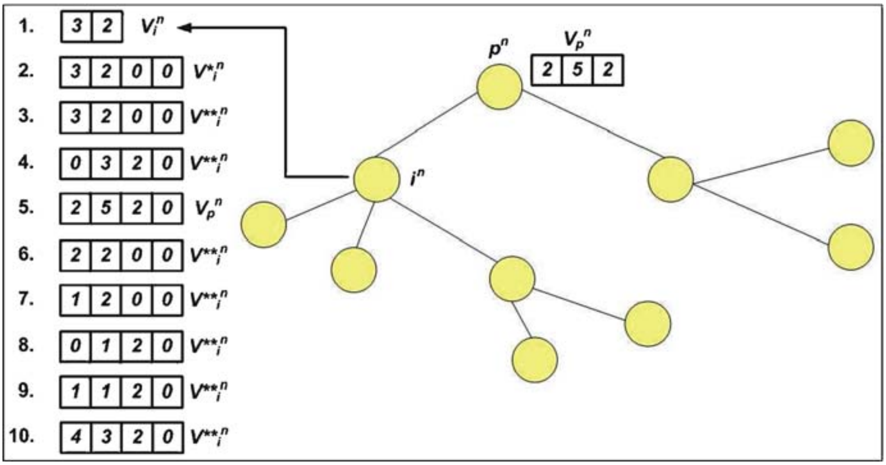


Fig. 4 Operations computed by a generic child i^n of the PAN coordinator p^n at the beginning of iteration n of the procedure PANEL. The numbers near the vectors indicate the corresponding steps of Pseudo-code 1

After receiving these data from all its children, p^n computes the best (i.e., the minimum) values of g and L (indicated with *bestMeanLevel* and *bestTreeDepth*, respectively), taking into account also its own values. Then, it creates a set M, where it puts, among all its children, the generic node i^n iff:

1. g_{i^n} is equal to *bestMeanLevel*
2. L_{i^n} is equal to *bestTreeDepth*

These conditions guarantee that if a new potential PAN coordinator is effectively chosen among the children of p^n, it will be characterized by the optimal (i.e., the minimum) values of g and L. After performing this phase, p^n checks if the set M is empty or not. If M is empty, this means that there are no nodes, among the children of p^n, able to improve network performance if elected as PAN coordinator, so the procedure stops and p^n is effectively elected PAN coordinator of the network ($p^{\mathrm{FIN}} = p^n$). In the other case, instead, among all nodes in M, p^n selects as new potential PAN coordinator (indicated as *potentialPANCoordinator*) the node that guarantees the best network balancing; we define the best network balancing as the minimum difference between the number of the descendants (f_{i^n}) of a node i^n and the number of the other nodes ($N - f_{i^n} - 1$) in the tree. After this choice *potentialPANCoordinator* becomes the PAN coordinator at the beginning of the iteration $n + 1$ and the procedure goes on.

The conditions present in PANEL are justified by the fact that our goal is to move (downward the parent–child relationships) the PAN coordinator toward a part of the network characterized by a greater number of nodes and a high mean level of the same nodes. The movement will reduce the mean level of nodes and the tree depth, once the new PAN coordinator is elected, and the new topology will result in a tree having all branches more balanced, in terms of number of nodes and depth. As example, in the case of Fig. 2b, PANEL moves the PAN coordinator from node 4 to node 3.

5 Performance Analysis

A performance analysis of the proposed procedure has been carried out by testing it on different network topologies. Our aim is to understand how nodes distribute at different levels of the tree when PANEL is applied on already formed IEEE 802.15.4 networks with $N = 50$ and 100. For each value of N, we simulate N times the formation of the network by using NS-2 and by varying each time the position of nodes in the considered area. For each topology, we randomly choose the PAN coordinator and collect the distribution of nodes at different levels. Then, we apply PANEL on formed networks and we collect the resulting distribution of nodes at different levels. Figure 5a, b show the obtained results for $N = 50$ and 100,

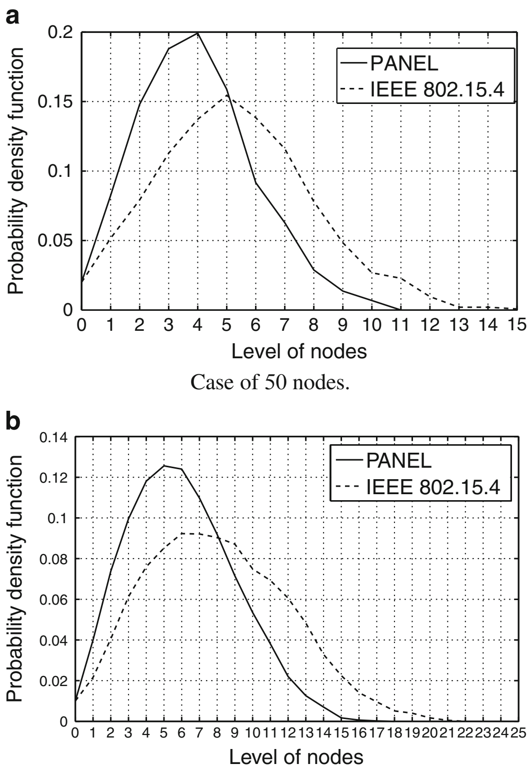


Fig. 5 Probability density function of nodes' level

respectively. In both cases, PANEL obtains improvements in the topology. In fact the curve that represents the probability density function of nodes' level related to topologies obtained with PANEL becomes higher and stamps out if compared with the one related to topologies obtained with the IEEE 802.15.4 association procedure. This means that by applying PANEL, the probability to find nodes at levels close to the PAN coordinator becomes higher when compared with the case of IEEE 802.15.4 networks. Therefore, there is an improvement of network performance, since in average shorter paths arise from sensor nodes to the PAN coordinator compared with the case of IEEE 802.15.4 networks: this results in energy saving and low data delivery delay within the network.

The improvement of network performance is confirmed from Figs. 6 and 7. They show, respectively, the average gain in terms of tree depth and mean level of nodes as function of the number of nodes in the topology, for the same networks previously analyzed. The gain of Fig. 6 is computed as the difference between the initial tree depth of topologies formed by using NS-2 (i.e., formed in accordance with the IEEE 802.15.4 procedure), and the tree depth achieved by PANEL. In the same way, Fig. 7 shows the gain in the mean level of nodes. Basically, the average value of this gain, in both cases, is always positive, thus confirming the goodness of PANEL and it

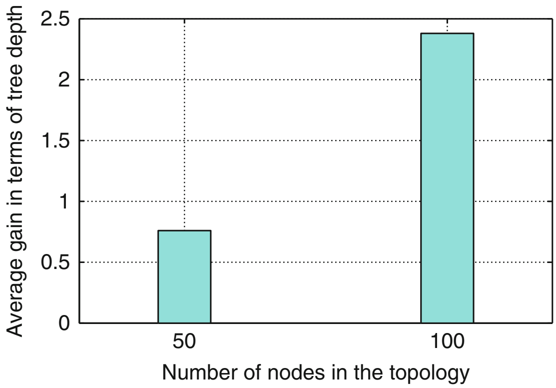


Fig. 6 Average gain in terms of tree depth as function of the number of nodes in the topology

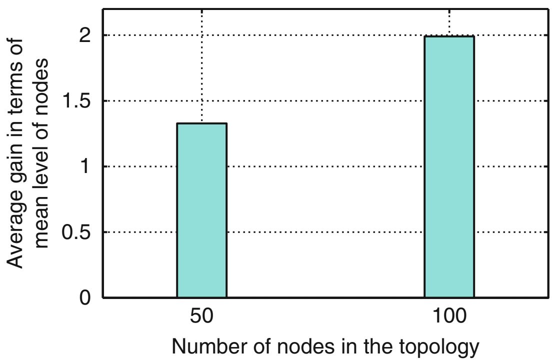


Fig. 7 Average gain in terms of mean level of nodes as function of the number of nodes in the topology

increases when the number of nodes increases. Therefore, PANEL reconfigures the network resulting in lower tree depth and mean level of nodes compared with IEEE 802.15.4, with a consequent improvement of network performance.

6 Conclusions

In this chapter, we presented a distributed solution, called PANEL, for PAN coordinator election in IEEE 802.15.4 WPANs. It can be efficiently applied in emergency scenarios, when it is required that this kind of network is able to self-configure and to guarantee a high lifetime and low data transfer delays. We showed that if a specific node assumes the role of PAN coordinator, network performance has a significant improvement.

PANEL works well in whatever network configuration, requires the exchange of simple control information and is compliant with the standard IEEE 802.15.4. For these reasons, it is suitable to be applied in emergency scenarios.

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